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Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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FLUIDIZATION AS A GEOLOGICAL PROCESS, AND ITS BEARING ON THE PROBLEM OF INTRUSIVE GRANITES

DORIS L. REYNOLDS

ABSTRACT. Fluidization is an industrial process in which gas is passed through a bed of fine-grained solid particles in order to facilitate mixing and chemical reaction. At a particular rate of gas flow the bed expands and the individual particles become free to move. With increase in the rate of gas flow a bubble phase forms and travels upwards through the expanded bed in which the particles are violently agitated; the bed is now said to be fluidized. With continued increase in the rate of gas flow more and more of the gas travels as bubbles containing suspended solids, until ultimately the solid particles become entirely entrained and transported by the gas.

As a consequence of the commercial importance of fluidization, experimental data have become available concerning the properties of gas-solid systems, and by reference to these it is apparent that fluidization has important geological applications. As a volcanic process fluidization is exemplified by the upsurging gas phase at Vesuvius, by farinaceous lava flows, and by tuff flows (ignimbrites) like those of the Valley of Ten Thousand Smokes. As a mixing process it is concerned in the evolution of suites of rocks characterized by discordant mineralogy and straight-line variation diagrams (e.g. Katmai and Montserrat). As an intrusive process it is exemplified by a conglomerate dike intruding dolerite near New Haven, by the Sudbury breccias, by the contents of the Swabian tuff pipes, and of some British Tertiary vents and fissures, by the pseudotachylyte and enstatite-granophyre of the Vredefort area, and by the intrusive granophyres of Slieve Gullion.

The geological examples of intrusive fluidized systems are characterized by net veins of non-dilational type, by breccias in which many of the fragments, even when derived from the adjacent wallrocks, are rounded as if by sandblast, and by mechanical hybrids. The evidence on which Daly based his conclusion that the granites of plutons were emplaced by magmatic stoping is examined and found to be more consistent with stoping by a system of fluidized solid particles than with stoping by a melt. The negative gravity anomalies characteristically found over granite plutons are inconsistent with emplacement by magmatic stoping, whereas they are readily explicable if the granites originated as fluidized country rock under conditions appropriate for chemical reactions.

THE INDUSTRIAL PROCESS OF FLUIDIZATION

During the last decade a process known to industry as "fluidization" has found steadily increasing application to large-scale industrial operations, e.g. in the catalytic cracking of petroleum, the slaking of lime, and the gasification of coal. It was on this account that an imposing mass of experimental data, relating to the dynamics of gas-solid systems, was made available at a symposium held in 1948 under the auspices of the Industrial and Engineering Division of the American Chemical Society (Matheson, Herbst, Holt and others, 1949). In the process of fluidization gas is passed through a bed of fine-grained solid particles in order to facilitate chemical reaction. When the gas flows slowly through the bed it percolates without agitating the individual particles; such percolation takes place at velocities of less than 0.01 feet per second with particles measuring about 40 microns. When the gas flows more rapidly the bed expands, and the individual particles become free to move.

With further increase in the rate of gas flow the bed continues to expand until a stage is reached at which gas bubbles form and travel upwards through the expanded bed. At this stage the particles in the expanded bed are violently agitated and the bed is said to be fluidized. In a bed consisting of particles measuring 40 microns, bubble formation occurs when the gas flow has a velocity of 1 foot per second. Further increase in the rate of gas flow causes larger bubbles to form and pass with increasing frequency through the expanded bed. With continued increase in the rate of gas flow, more and more of the gas travels as bubbles until ultimately the solid particles become entirely entrained and transported by the gas.

At the time of bubble formation the fluidized bed consists of two phases: (1) a continuous phase, formed by the expanded bed, consisting of solid particles violently agitated by a small proportion of the total amount of gas passing through the bed, and (2) a discontinuous phase composed of rising bubbles which may contain suspended solids that are in consequence transported by the gas. On account of the turbulent movements of the particles in the expanded bed, and the emission of bubbles from its surface, the bed at this stage is sometimes referred to as a "boiling bed." The expanded bed has a definite, and roughly horizontal, upper surface, a measurable viscosity, and a density analogous to that of a liquid, so that objects of relatively low specific gravity will float on its upper surface. The density, which attains its maximum before many gas bubbles begin to form, is measured by reference to the pressure drop over the bed, and the viscosity is determined by the same methods as those devised for measuring the viscosity of liquids. Both the density and viscosity of the expanded bed increase with the density and size of the component particles. For a given material, however, the viscosity is lower when the particles are of uneven size, and the addition of even a small percentage of exceedingly fine-grained material to a bed of coarser-grained particles increases the mobility very markedly.

The importance of fluidized systems in industrial processes is that the turbulent expanded bed provides ideal conditions for chemical reaction between gas and solid. This depends both on the intimate contact that obtains between gas and fine-grained solid particles, and on the maintenance of an approximately uniform temperature throughout the fluidized system. The latter, determined experimentally, depends on the fact that the solid particles act as reservoirs and carriers of heat, their violently turbulent motion enabling them to absorb heat in one part of the system and to release it in another. The actual temperature of a fluidized system naturally depends on the rate at which heat is transmitted to and lost from the system. A further advantage of fluidized systems in industrial operations is the ease with which the materials can be transferred from one container to another by increasing the velocity of the gas and entraining the particles. The turbulent expanded bed also provides ideal conditions for mixing solid particles. Experiments have shown, for example, that the agitation and turnover of solid particles by water is insignificant in comparison with the rapid rate of circulation and mixing in the turbulent expanded bed of a solid-gas system.

In industrial processes it is obviously advantageous to reduce erosion of the vessels containing fluidized systems to a minimum, and some of the factors that control erosion by gas-solid particle streams have, in consequence, been evaluated experimentally. It has been found, for example, that in blasting iron with silica sand the maximum erosion occurs when the angle of impingement is 20° measured from the surface of the iron. The rate of erosion of the iron increases rapidly with increase in the angle of impingement from 0° to 20°, and then slowly decreases to about half the maximum at 90°.

The fine particles used in industrial fluidized systems are commonly used over and over again as catalytic agents, and it is therefore desirable to reduce their attrition to a minimum. Experiments have consequently been made to determine the attrition characteristics of particles of different sizes and shapes. It has been found, as would be expected, that tiny particles with a spherical form resist abrasion most effectively.

Although in industrial operations the term "fluidization" is applied specifically to gas-solid systems, it is strictly also applicable to a suspension of solid particles in an upward flowing stream of liquid which has a lower density than that of the particles. The solid particles become dispersed within the flowing liquid, and an expanded "quiescent fluidized bed" is formed, within which there is agitation but little or no mixing of the solid particles (Lewis and Bowerman, 1952). If the particles fluidized by liquid vary in size, elutriation occurs. It is important to realize that the bubble phase of gas-solid systems has no counterpart in liquid-solid systems and that the turbulent expanded bed is, in consequence, specific to gas-solid systems. This is of importance to the geologist because, from recognition of turbulent expanded-bed phenomena—e.g. the association of turbulent flow structure with abraded and well-rounded rock fragments which have not been appreciably transported away from their source rock, together with a lack of grading of the fragments concerned, and the possible presence of druses—it can be inferred that the fluid agent was gas and not liquid.

Closely allied in mechanism to the process of fluidization of solid particles by gas is the method of painting by spraying. Compressed carbon dioxide or air is pumped through a liquid preparation of cellulose lacquer, and the resultant spray is played over the surface to be painted. So highly mobile is the stream of expanding gas, charged with droplets of cellulose lacquer, that the surface of a motor car or other object can be smoothly and evenly covered with a thin layer that readily penetrates cracks and crevices that could not be painted with a brush.

In this paper the term "fluidization" is used, as in industry, to indicate solid particles supported by gas but, for convenience of writing, it will be extended to include the few examples where the particles borne by gas were or may have been liquid, i.e. spray.

GEOLOGICAL EXAMPLES OF FLUIDIZATION

Extrusive Fluidized Systems

Although the term "fluidization" has not previously been used in relation to geological processes, the process implied by this industrial term is a

well-known volcanic one. In the uprushing gas phase (Perret, 1924) of the 1906 eruption of Vesuvius, for example, the conduit of the volcano was eroded and widened by fluidized solid particles. On the other hand fluidization of liquid lava is exemplified by that rare type of non-continuous lava flow (Perret, 1950) that has been seen to emerge like farinaceous grains. Writing of such a flow, observed by him on September 4, 1908 in Halemaumau, Brigham (1909, p. 213-214) records: "In the centre of the pit was a curious break running east and west, at the edge of which was a vertical slab of lava, semicircular in form, resembling half a mill-stone, and other slabs continued the wall for some distance. Over these fell a cascade of lava in a condition I had never before seen; its particles seemed to be in a state of mutual repulsion, and although white-hot, fell through the central hole of the 'millstone' as meal." Similarly, in describing the various appearances of lava issuing from Vesuvius, Hamilton (1773) relates: "I have seen it farinaceous, the particles separating as they force their way out, just like meal coming from under the grindstone."

Katmai area.—Examples of volcanic fluidized systems on a catastrophic scale are to be found in the various descriptions of nuées ardentes and incandescent tuff flows: ignimbrites and tuff remaining as products of such fluidization. Particularly pertinent is Fenner's (1937) inference from the evidence relating to the deposit of ash and pumice in the Valley of Ten Thousand Smokes (Alaska). This deposit differs from the products of normal ash falls in the following ways: (1) it is restricted to topographic depressions; (2) vegetation engulfed by it is carbonized, and there are indications of bush fires that can only be explained by supposing that the tuff emerged with a high temperature; (3) along the sides of the deposit, and on the hillslopes facing the valley it occupies, the trees lean at a high angle as if blown over by an accompanying violent wind. Fenner infers that the pumice and ash, instead of being violently thrown into the air, "boiled over", and rushed down the valley as an "outward-spreading and forward-moving torrent of incandescent sand and pumice, each particle of which was surrounded by and partially suspended in gases." The pumice and ashes were evidently poured out as fluidized solid particles and, as Fenner concludes: "In this condition the mixture exhibits the lack of cohesion and readiness to flow that characterize liquids." In the lower part of the Valley the sand flow or ignimbrite has little coherence, and "the fine fragments have the characteristic angular and cusp-like forms of glass shards produced by the disruption of bubbles" (Fenner, 1937, p. 236). The upper part of the sand flow, however, where the temperature was higher, is not only firmly consolidated but, as a consequence of minute crystals having grown from the glass, it has a felsitic appearance. Fenner (1937, p. 256) records that "a thin section of this material shows, instead of individual shards, a slightly turbid aggregate, permeated by innumerable tiny to cryptocrystalline growths of secondary minerals. In places, these little crystals may be seen, even with the hand lens, encroaching upon small lumps of included glass and replacing them. By further action of this sort the glass has disappeared, and little nests of crystals are left. Where determinable, these are mostly of tridymite and orthoclase."

In the vent of Novarupta, in the upper part of the Valley of Ten Thousand Smokes, is a lava dome consisting of rhyolite charged with blocks, clots and drawn-out bands of basic andesite which Fenner regards as having probably been derived from piles of morainic material which lay on the Valley floor at the time when Novarupta became active. Scattered over the present Valley floor are pieces of pumice characterized by similar clots and drawn-out bands of andesite, but Fenner records that within some of the specimens of pumice there is a fairly even mixing of phenocrysts of pyroxene and basic plagioclase derived from the andesites, with phenocrysts of quartz and albitic feldspar derived from the rhyolite.

Fenner interpreted these phenomena as a consequence of melting of andesite by rhyolite lava, whereas Howel Williams (1953) has suggested that rhyolite and andesite lava foamed simultaneously from feeding fissures and became partially mixed. Andesite melt derived by fusion of solid andesite can only be supposed to have been viscous, and foams are particularly viscous, so that both Fenner's and Williams' hypotheses would equally well account for the interbanding of rhyolite and andesite, a phenomenon indicative of the mixing of viscous materials, or of finely fragmented solids (e.g. in some mylonites). However, the even mixing of phenocrysts, derived partly from rhyolite and partly from andesite, implies a state of high mobility with which neither Fenner's nor Williams' hypothesis is compatible.

If the rhyolite of Novarupta, like the ignimbrite of the Valley, was erupted as particles fluidized by gas, the gas having a temperature high enough to fuse the groundmass of andesite, then the two seemingly opposed phenomena, the one implying mobility (e.g. spray) and the other viscosity (e.g. foam) of the materials concerned, could be accounted for as successive stages in a time sequence. The rapid rate of circulation and mixing of particles in a turbulent expanded bed would adequately account for the even distribution of phenocrysts of different origins seen in some of the specimens of pumice. At a later stage, under surface conditions, the fluidizing gas would be lost, leaving the gas held in solution in the melts to be partly liberated as bubbles. In these circumstances simultaneous flowage of andesitic and rhyolitic foams would account for the banded structures.

The "boiling over" and downrush of the "incandescent tuff" or ignimbrite flow of the Valley of Ten Thousand Smokes is possibly to be compared with the liquid-like expanded-bed phase of fluidization, whereas the phenomena of Novarupta, which imply loss of the fluidizing gas on eruption, suggest that here, before eruption, the expanded-bed phase was succeeded by an increased rate of gas flow sufficient to promote complete entrainment.

In the pumice ejected from the main crater of Katmai (Fenner, 1926), basic rocks similarly provided the xenoliths, and here again an even distribution of discordant minerals is a characteristic feature. A further example of discordant mineralogy in rocks deposited by nuées ardentes is found in the blocks of labradorite-dacites (bandaites) described by A. G. MacGregor (1938) from Montserrat. Reference should here be made to the detailed petrographic study of the minerals in the Tertiary volcanic rocks of the San Juan region by Larsen, Irving, Gonyer, and Larsen (1936, 1937, 1938) whereby

it was shown that phenocrysts of quartz, sanidine, pyroxenes and "many if not most of the plagioclase phenocrysts" did not crystallize from magmas of the compositions of the lavas in which they are found. The investigators favor the conclusion that the mineralogical discordancies are a sign that in the ancestry of the lavas there has been mixing of two magmas, either or both of which had suspended crystals. Impressed, however, by the uniformity of the lava flows, some of which are very large, and by the uniformity even of great groups of flows, they reach the final conclusion "that there must have been some means to mix thoroughly large bodies of magmas before eruption" (Larsen, Irving, Gonyer and Larsen, 1938, p. 256). By reference to the evidence of the Katmai rocks, it may be suggested that the mixing depended on pre-eruption fluidization of the materials by gas with an appropriately high temperature.

Straight line variation diagrams.—If rocks with discordant mineralogy are correctly interpreted as mechanical mixtures (one might call them mechanical hybrids), then—provided there has been no appreciable chemical change—the chemical analyses of individual suites of such rocks should form straight-line variation diagrams. This is true for the Katmai region (Fenner, 1926, p. 700), and for Montserrat (MacGregor, 1938, table 3, p. 74). Straight-line variation diagrams have always been a puzzle (Fenner, 1926, p. 768-771; 1938), so much so that Bowen (1928, p. 114-122) attempted to discredit the straight-line diagram for the Katmai area, because straight-line variation diagrams are inconsistent with crystal differentiation. Where other evidence is lacking they may in future provide criteria for recognizing mechanical mixing by fluidization in the ancestry of rock suites.

Gardiner River area.—Perhaps Fenner's (1938) remarkable discoveries in the Gardiner River, Yellowstone Park, may eventually find a solution along these lines, since the variation diagram is here again of the straight-line type. If the Gardiner River rhyolite flow is in reality a crystalline derivative from an incandescent flow of fluidized particles deposited as ignimbrite, then the astonishing effects that this flow had on the solid basalt of its floor and walls become understandable. Moreover, the further evidence recorded by Wilcox (1944), which led him to think that basalt and rhyolite had been fluid at the same time, finds an explanation. Supporting evidence is provided by: (1) the penetration of basalt by extremely narrow veins of rhyolite, sometimes many feet long, the materials of which could only have been emplaced in a highly fluid state, e.g. by expanding gas; (2) the presence of druses within both the veins and the main body of rhyolite, cf. the expanded bed of industry through which a bubble phase rises; and (3) the lack of reaction minerals within the mixed rocks such as would inevitably be present if the rocks had been products of mixed magmas or lavas.

Intrusive Fluidized Systems

Conglomerate dike in dolerite, New Haven.—A small-scale geological example of a fluidized system in which the gas was water vapor with a temperature of the order of 575° C. is to be found in Walton and O'Sullivan's (1950) account of a dike of Triassic conglomerate penetrating a dolerite sill

from below. The dolerite sill, situated near New Haven, Connecticut, is about 300 to 400 feet thick, and overlies Triassic arkosic conglomerate characterized by quartz pebbles, up to 2 inches across, and grains of pink feldspar. The conglomerate dike is continuous with the conglomerate underlying the sill, and is composed primarily of the same materials. At its base it is 3 to 4 inches wide, but it narrows upwards, being only 0.01 inches wide 30 feet above its base. Within the dike the quartz pebbles are commonly relatively big enough almost to bridge the channel. Eight feet above its base the conglomerate dike splits into divergent offshoots, two of which converge again, like net veins, so as to enclose an angular block of the dolerite. Of high significance is the fact that a small but appreciable proportion of the conglomerate dike is made up of drusy cavities. Attached to the walls of these druses, and associated with calcite, are well-formed prismatic crystals of quartz, clusters of radiating acicular crystals of epidote, small nodules of chlorite, minute well-formed crystals of pyrite and garnet, and a few small crystals of sphene. As Walton and O'Sullivan conclude, the dike "proves beyond question that under the proper physical conditions loose aggregates of solid material can be injected in a manner entirely similar in final effect to fluid injection." In short, part of the conglomerate underlying the sill became fluidized. Water, trapped in the sediments beneath the sill, was vaporized by the heat of the dolerite intrusion. In response to a local fall in pressure, caused by fracturing of the sill, the water vapor expanded and "brought the solid material in the conglomerate into a momentary state of suspension and it was swept into the fracture as a suspensoid" (Walton and O'Sullivan, 1950, p. 10). The absence of flow textures within the dike (Walton and O'Sullivan, 1950, p. 11) indicates that the solid particles composing it were not entirely entrained, while the presence of druses suggests comparison with the rising bubble phase of the expanded bed of industry, within which the solid particles have a turbulent motion.

Facts of particular importance concerning the fluidized conglomerate dike are: (1) The presence within the druses of well-formed crystals of minerals containing Si, Al, Fe, Mg, Ca and Ti, indicating that these materials diffused through the water vapor. (2) The metamorphism of the dolerite, for a distance of 3 mm, adjacent to the conglomerate dike. Serpentinous alteration of the pyroxene becomes more abundant within this zone until, within 1 mm of the contacts, the pyroxene is completely altered to antigorite. Some of the plagioclase is also slightly altered within the contact-altered zones of the dolerite, and chlorite and quartz make their appearance as interstitial minerals at the immediate contacts. A quartz-dolerite hybrid is thus formed as a consequence of diffusion of Si through the gas phase of the fluidized solid system that penetrated the dolerite. (3) The presence of a microscopic inclusion of contact-altered dolerite in the conglomerate dike, composed of antigorite and plagioclase, with an indistinct form as a consequence of mechanical disintegration.

The penetration of dolerite sills in other localities by rheomorphic veins of sedimentary origin is a well-known phenomenon (Harris, 1937; Mountain, 1935, 1936, 1944; Walker and Poldervaart, 1942, 1949), and the conglom-

erate dike possibly provides a clue as to their mode of emplacement. In some of these examples the rheomorphic veins have been transformed to granophyre as a consequence of addition of elements such as Ca, Fe, Mg and Ti, and subtraction of Si. Granted that the added constituents were diffusing through the water vapor by which the sedimentary particles were fluidized, as is known to have been the case when the New Haven conglomerate was fluidized, then all that was required for chemical reaction to take place between these constituents and the initial sedimentary material was an appropriate composition for the latter and an adequate temperature. The geological evidence shows the resulting product to be granophyre.

Swabian tuff pipes.—Hans Cloos' (1941) investigation of the Swabian tuff pipes provides evidence of relatively large-scale intrusive fluidized systems. The Swabian tuff pipes contain two widely different types of material: (1) blocks of rock and tuff derived from the Jurassic rocks through which the pipes are drilled, and (2) lapilli of melilite-basalt. Prior to Cloos' work the contents of these pipes were thought to have been hurled into the air by violent explosive activity and to have fallen back into the vents with a haphazard arrangement. By mapping the dip and strike of blocks of Jurassic rocks within the pipes, however, Cloos demonstrated that the structure is continuous from one mass to another over wide areas. Although the disconnected blocks of Jurassic rocks within the pipes occur at a lower level than their true stratigraphic horizon, their relative orientation is undisturbed, and it therefore cannot be supposed that they became disconnected as a result of violent explosive activity. Cloos showed that the blocks reached their present position as a consequence of gentle subsidence relative to the tuff

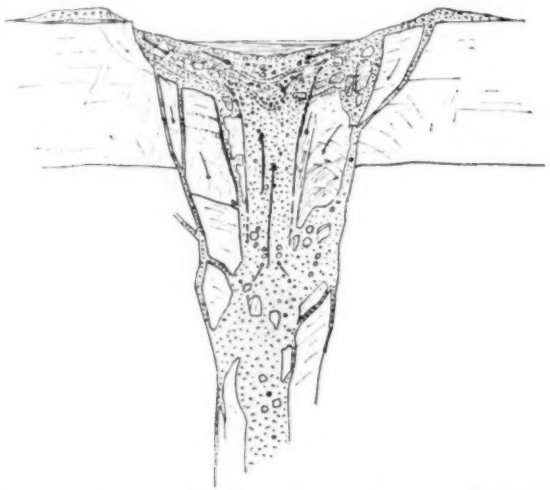


Fig. 1. Reconstruction of a Swabian tuff pipe. Gray = upflowing melilite-basalt tuff with small fragments of the neighboring Jurassic rocks. White = massive blocks of Jurassic rocks, detached from the wallrocks, subsiding in the rising gas-tuff streams. Reproduced from H. Cloos (1941, fig. 35, p. 785).

which surrounds and veins them. His explanation is that gas, charged with lapilli of melilite-basalt, escaped upwards through structural breaks and cracks in the Jurassic rocks. Small particles of the wallrocks, detached by the erosive action of the rising streams of lapilli-charged gas, were carried upwards by the latter and enhanced their erosive power. In this way initial cracks were persistently widened until eventually massive blocks of Jurassic rocks became detached from the wallrocks, and engulfed within the slowly rising gas-tuff streams (fig. 1). By the penetration, i.e. intrusion, of the highly mobile gas-tuff mixture along structural breaks and cracks within the major blocks, the latter became still further dissected until they finally acquired their present-day appearance of an assemblage of fragments. The fact that the major blocks sank without relative disorientation of their component parts suggests that the gas-tuff mixture within which they subsided resembled the expanded fluidized bed of industry; the massive blocks subsided as if in quicksand. Finally, in the later phases of volcanic activity, veins of tuff, now seen cutting both the contents of the pipes and the wallrocks, were emplaced by rising gas streams.

The fine-grained intrusive pyroclastic rocks of the Swabian tuff pipes Cloos termed "tuffisite." This name will have a useful application, not only in distinguishing between intrusive tuff (tuffisite) and the more familiar extrusive variety but also for distinguishing crosscutting pyroclasts from cataclastic rocks.

Evidence of further importance from the fluidized systems of the Swabian tuff pipes is that in one of them (Cloos, 1941, p. 729, and fig. 15, p. 728) there are sharply defined inner and outer zones. The outer zone consists of tuff derived mainly from the Jurassic wallrocks and includes relatively few lapilli of melilite-basalt. Within this outer zone of tuff large inclusions of Jurassic limestone derived from the adjacent wallrocks are embedded. In the inner zone, the tuff contains larger and more numerous lapilli of melilite-basalt but only small inclusions of the Jurassic wallrocks. The junction between the outer zone of tuff and the wallrock is vertical and sharp, and similarly the junction between the two zones of tuff is vertical and sharp. This occurrence provides important evidence of the existence not only of mixed, or hybrid, intrusive pyroclasts but also of sharp contacts between such pyroclasts. The inner zone, containing the higher proportion of material from a deeper level, was evidently the region of most rapid flowage of the gas-tuff stream, whereas the outer zone, containing the higher proportion of tuff derived from the wallrock, was a relatively stagnant zone of tuff formation.

Breccias of Sudbury.—Further examples of the fluidization of solids are provided by the breccias of Sudbury, Ontario. The breccias, composed of fragments embedded in a matrix of comminuted but recrystallized rock, occur as steeply dipping dike-like masses measuring up to several miles in length, and from a few feet up to a mile in width. The fragments vary in size, being commonly less than 2 feet in diameter, but they may be larger, one as large as 2600 feet by 900 feet having been recorded from the Frood breccia (Yates, 1938). The smaller of the fragments are commonly sub-rounded or rounded. Both fragments and matrices composing some of the breccias are derived

almost entirely from the adjacent wallrocks, whereas in other examples fragments and matrices alike differ from the adjacent wallrock and have sometimes been transported many thousands of feet. Moreover, the penetration of small crevices by finely fragmental material (Fairbairn and Robson, 1942) provides evidence of high mobility such as characterizes fluidized solid particles.

By detailed study of some of the breccias, including petrofabric and chemical analyses, Fairbairn and Robson (1942) have thrown light on their origin. Although the mica flakes within the matrices of some of the breccias are aligned, petrofabric analyses demonstrate that the quartz has very little or random orientation. Indeed the quartz is less well oriented in the matrix materials than it is in the rocks from which the latter were respectively derived, thus suggesting that there was low confining pressure at the time when the breccias were formed.

From a consideration of all the evidence, for the details of which the reader is referred to the source paper, Fairbairn and Robson conclude that the breccias were formed as a consequence of the permeation of fluids, possibly gases under high pressure, along structural breaks. "Fragments large and small were torn loose from the walls and gradually comminuted by joint action of the steam and movement. In time a mobile matrix formed which attained sufficient volume to transport the remaining solid fragments. . . . This breccia 'mud', saturated with water under high temperature and pressure, was able to penetrate small crevices for scores of feet. A permanent record of its flow is preserved in the dimensional orientation of mica flakes which it carried along. These follow faithfully the boundaries of fragments or form swirls and small folds in the matrix" (Fairbairn and Robson, 1942, p. 31).

Not only do Fairbairn and Robson demonstrate that the breccias were formed as a consequence of what may now be termed fluidization but they also provide evidence that chemical reaction took place between the fluidizing medium and the finely comminuted matrix material (tuffisite), just as would be expected by reference to the industrial process of fluidization. In order to compare the chemical composition of fragments with that of matrix material derived from the same source, three pairs of chemical analyses were made, namely, of Ramsay Lake grit and its breccia matrix, of Mississippi quartzite and its breccia matrix, and of Sudbury gabbro and its breccia matrix. All three pairs of chemical analyses show that the finely comminuted material forming the matrices of the breccias has been slightly altered in composition, the most marked change being enrichment in soda. Further than this Fairbairn and Robson also find that when the chemical analyses are plotted as variation diagrams (on a silica base) the lines representing correlated pairs of analyses (fragment and matrix) converge. They consider that the composition toward which the lines converge represents what would have been the state of equilibrium—had there been time for its attainment—under the conditions existing when the breccias were formed. Although two of the breccias were derived from rocks of sedimentary origin, the supposed equilibrium composition, as Fairbairn and Robson point out, has relative pro-

portions of constituents corresponding to those of an igneous rather than a sedimentary rock.

Further points of chemico-mineralogical importance are that Fairbairn and Robson find hydroxyl-bearing minerals, e.g. chlorite, sericite, and epidote-clinozoisite, to be more abundant in the matrices than in the fragments, and margins of fragments to be locally richer in hydroxyl-bearing minerals than the cores.

Bull-Domingo breccia.—In a recent description of the Bull-Domingo breccia, south-central Colorado, Peters (1953) records characteristics which are incompatible with its having originated as an explosion breccia as was previously supposed (Gabelman, 1953). The breccia, or agglomerate, as Peters prefers to call it, fills an irregular pipe about 100 to 200 feet in diameter which branches upwards. It is composed of boulder- and pebble-like fragments embedded in a compacted matrix of fine-grained fragments, all the materials of which have been derived from the Precambrian rocks transgressed by the pipe. Not only have the fragments been rounded by attrition within the pipe, but the various rock types, namely, gneiss, syenite, and pegmatite, have been so thoroughly mixed that they occur in about the same proportion among "boulders," "pebbles," and matrix alike, and this composition appears to be maintained throughout the 1000 feet of known depth of the pipe. Peters records, moreover, that the rims of nearly all the boulders are altered, the rims being thickest in the vicinity of ore shoots, thus "indicating association with mineralization." All these phenomena are exactly what would be expected if the agglomerate were formed by fluidization, and Peters is no doubt very near the mark when he infers that "blocks loosened from the walls were churned by convection in a medium of finer rock fragments," and supposes that the "agglomerate pipe represents a boiling spring which formed in an area of intersecting faults and was enlarged to its present size by churning rock debris." Gas, however, would be a more efficient agent than liquid—even a boiling liquid.

It is a point of economic interest that ores are associated with both the Sudbury and Bull-Domingo breccias.

Tertiary agglomerate vents, Northern Ireland.—The agglomerates of the Forkhill vents (Richey, 1932; Reynolds, 1951b), which form part of the Tertiary ring complex of Slieve Gullion, Northern Ireland, in many ways resemble the breccias of Sudbury and Bull-Domingo. As long ago as 1878 Nolan wrote of these fragmental rocks: "That this rock is of volcanic character, somewhat analogous to volcanic agglomerate, we can scarcely entertain a doubt. Nevertheless, it differs from the usual type of this rock, as it is . . . . almost altogether composed of pieces of non-volcanic rocks, these fragments being pre-existing crust . . . . and varying accordingly—granitic agglomerate prevailing in those portions that were occupied by that rock—a mixture of slate and granite about the junction of these formations, and slate fragments almost exclusively in the Silurian district." The most puzzling thing about these agglomerates is that their closely packed blocks, ranging up to about 2 feet across, are so well rounded that they would undoubtedly have been regarded as conglomerates if they were not filling arcuate vents.

Furthermore, quartz grains within the matrix tuff, derived by fragmentation of Caledonian granodiorite, are not only commonly rounded but also sometimes have glazed surfaces indicative of attrition. These phenomena remain unexplained if the vents are regarded as of purely explosive origin, but they are adequately accounted for as a consequence of abrasion within a turbulent expanded bed. Embedded in the agglomerates of the vents, as recorded by Richey (1932), there are large masses of basaltic lavas, up to about a quarter of a mile in length, which, like the massive blocks of Jurassic limestone within the Swabian tuff pipes, have subsided from higher levels. Re-examination of these masses of basalt has revealed that they have themselves been fragmented and fluidized so that what appear to be at first glance homogeneous masses are actually aggregates of fragments, some of which have a boulder-like form, embedded in and penetrated by fine-grained, black basaltic tuffisite. Moreover, within these aggregates there are occasional boulder-like forms of Caledonian granodiorite that were evidently introduced at a time when the fragmented basalts formed expanded beds. Where these basaltic aggregates adjoin the normal agglomerate they are invaded by relatively leucocratic veins composed of a mixture of rounded grains of both basalt and Caledonian granodiorite, together with quartz derived from the latter rock. One is again reminded of the fact that in industrial processes fluidization by gas provides ideal conditions for mixing solid particles.

In a recent investigation of some of the Tertiary vent agglomerates of the Antrim plateau (Northern Ireland) Patterson (1952) finds that they are composed of fragments derived from the vent walls, some of which have sunk from higher levels, whereas others have been transported upwards from lower levels by rising gas streams. Patterson considers the contents of the vents to have been comminuted and ball-milled by ascending gas streams, the temperature of which appears to have been comparatively low. Of special interest is the fact that not only have rounded blocks of olivine-basalt been introduced into shattered chalk near vent margins but this chalk-basalt agglomerate actually intrudes the relatively undisturbed chalk as ramifying dikes.

From the central volcanic complex of Arran, King (1953) has recorded the details whereby tuffisite, comparable with the matrix material of the agglomerates just described, originated as a consequence of separation, rounding, and corrosion of the constituent minerals of a gabbro, parts of which were finely comminuted. The tuffisite so formed intrudes the adjacent undisturbed rocks, sometimes as minute veins in which the fragments practically span the channels. King attributes the fragmentation of the gabbro to the upward flowage of gas, possibly along structural breaks, and envisages the tuffisites as having existed as a gas-solid suspension in which the solid particles possessed varying degrees of motion. Apart from the cracking and annealing of some of the plagioclase crystals there is no evidence as to the temperature of the through-flowing gas.

Fissures of fumerole action, Rhum.—The "fissures of eruption and solfataric action" described by Harker (1908) from the Island of Rhum in the Inner Hebrides provide further evidence of fluidization. The Torridonian sandstone is here traversed by vertical bands within which the sandstone has

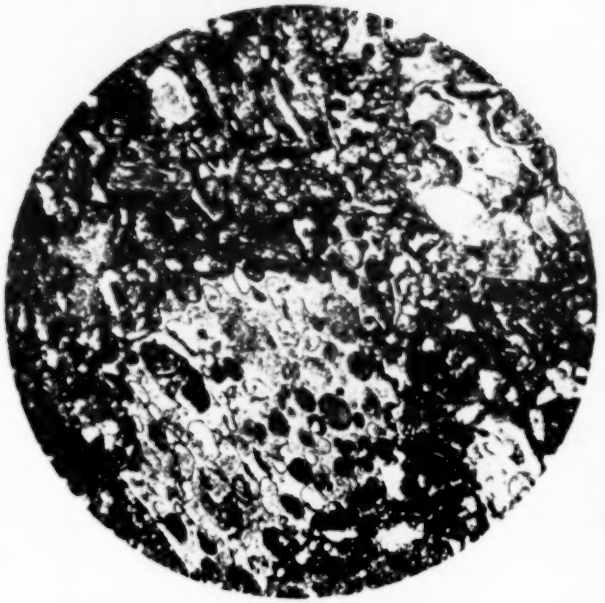
been thermally altered and commonly fragmented. In one or two occurrences bleaching of the sandstone within the limits of the band is the only change, but more often the sandstone is brecciated, and in some cases it has been subjected to so high a grade of thermal metamorphism as to present a "quasi-spherulitic appearance due to a stellate disposition of the recrystallised felspar" (Harker, 1908, p. 62). This may be a rudimentary stage in the transformation of sandstone to granophyre such as was completed in the rheomorphic veins referred to above. Recrystallization of the sandstone is confined to the bands themselves which are thus sharply marked off from the undisturbed and unaltered red sandstone bordering them. Harker attributes the thermal alteration to "some kind of *solfataric agency* operating along vertical bands of rocks disintegrated by crushing" (1908, p. 66). The fragmentation of the sandstone within the bands cannot be attributed to mechanical crushing, however, because the sandstones transgressed by the fragmented bands are undisturbed and exhibit "no displacement of the nature of faulting" (Harker, 1908, p. 62). Moreover, within some of the bands the sandstone fragments have a rounded form. When considered in conjunction with the other evidence cited in this paper it would seem that the fragmentation of the sandstone within the bands and the rounding of the separated pieces are better accounted for as a consequence of abrasion dependent on attrition, erosion, and fluidization brought about by the escaping gas streams themselves, and that the thermal metamorphism within the bands provides a measure of the temperature of the gas.

Within parts of some of the breccia bands a gray rock, which appears to have crystallized from a melt, forms a matrix to the sandstone fragments. This rock Harker regards as basalt contaminated with sandstone, but the absence of evidence to show that it represents basalt magma is clear from his remark (1908, p. 65) that there is "no direct indication of its precise original composition." Indeed Harker's description of thin slices of the gray rock show it to be very different from basalt, and related to the highly metamorphosed sandstone in which the feldspars have recrystallized with a stellate form.

Tertiary vent of Glas Eilean, Ardnamurchan.—A Tertiary vent at Glas Eilean, near Kilchoan in Ardnamurchan (Richey, 1930, p. 131-133) provides evidence of fluidization similar in many respects to that displayed by the Swabian tuff pipes. The brecciated material within the Glas Eilean vent includes fragments of Moine schists, Mesozoic sediments, Tertiary basalt lavas, and cone sheets. Richey (1940, p. 171) records that the various rock types "are confined mainly to separate parts of the vent, where they would appear originally to have occurred," thereby indicating that there has been relatively little intermixture of the material within the vent. Masses of Jurassic limestone, traversed by cone sheets, provide evidence that the brecciation was not implemented by explosive activity alone, for of them Richey (1930, p. 131-133) records that there has been so "little relative movement of the brecciated fragments composing each mass . . . that the original relationship of the plexus of cone-sheets cutting the limestone can be easily made out." The explanation of the fragmentation of these masses of Jurassic limestone and their inter-

PLATE 1

A. Vein of ignimbrite with a fine-grained margin (dark) intruded into basalt lava (light). Glas Eilean vent, Kilchoan, Ardnamurchan. Photomicrograph, ordinary light, x 4.



B. Photomicrograph of the materials—glass shards and pumice —in the coarser-grained middle of the ignimbrite vein of plate 1-A. Ordinary light, x 45.

secting cone sheets is supplied by the presence of tuff between the fragments which Richey describes as infilling all the cracks and crevices of the breccias. This tuff is an intrusive ignimbrite, being "composed almost entirely of siliceous scoriaceous fragments and wisps of acid glass which show plainly the curvilinear form of glass fragments" (Thomas, in Richey and Thomas, 1930, p. 139-140). Veins of this intrusive ignimbrite, cutting the basalt of the vent walls some yards from the actual breccia, are described by Thomas as consisting "of a roughly laminated mass of minute chips of devitrified glass, some of the fragments showing well-defined fluxion structure, others being of the nature of disrupted pumice." The lineation of the tuff provides evidence that it was entrained in the gas streams, the velocity of which must, therefore, have been relatively high.

I am indebted to the Director of H. M. Geological Survey for allowing me to examine microscope sections (22237 and 22237 A and B) of the intrusive ignimbrite. A slice of an ignimbrite vein cutting the basalt wallrock several yards from the vent shows it to have a fine-grained marginal zone adjacent to the basalt (pl. 1-A). The tuff composing the marginal zone is so fine grained as to appear felsitic, but in the coarser-grained central part of the vein the larger particles are pieces of pumice, whereas the smaller have the curvilinear forms of glass shards (pl. 1-B). The zoning of the vein is probably to be accounted for by the fact that the most rapid flowage would occur in the middle of the vein where retardation by friction would be at a minimum. In consequence, relatively large particles would be transported in the middle of the vein and relatively small ones at its margins. Within the fine-grained marginal zone inclusions of basalt, isolated from the wallrock, are enclosed by the tuff, just as xenoliths would be in an igneous vein (pl. 1-A).

Of outstanding importance from a petrogenetic viewpoint is Richey's observation that to the unaided eye the ignimbrite veins "appear exactly similar to the net-veining characteristic of the margins of many ring-dykes in Ardnamurchan;" in illustration reference is made to a drawing (Richey, 1930, fig. 34, p. 257) of net veins of granophyre in the quartz-dolerite of a ring dike. Referring to the veins in the ring dike Richey (1930, p. 256) records: "These veins form reticulated patterns recalling the acid veinings characteristic of many intrusive margins in Ardnamurchan and elsewhere, to which the name 'intrusion-breccia' is applied." Some of the systems of net veins of granophyre are very extensive, even when composed of veins only a fraction of an inch in width, and their mode of emplacement has always been a puzzle. They become readily understandable, however, if their materials, like the glass shards of the ignimbrite veins of Glas Eilean, were emplaced by expanding gas which surged along cracks in the host rock.

Pseudotachylyte, Vredefort area.—Veins of pseudotachylyte, which sometimes—like the veins of ignimbrite in Ardnamurchan —assume a net form, were first investigated by Shand (1916) in the neighborhood of Parys where they ramify through granite with which they are chemically almost identical. Subsequently, Hall and Molengraaff (1925, p. 93-114) discovered that veins and dikes of pseudotachylyte are a common and widespread phenomenon

throughout the Vredefort area, and Willemse (1936) demonstrated that the composition of the pseudotachylyte is everywhere related to that of the rock it transgresses.

From microscopic and chemical evidence Shand concluded that the pseudotachylyte of Parys was derived, by fragmentation and partial fusion, from the granite it intersects. He showed, however, that the fragmentation was not caused by shearing, a conclusion that was confirmed by Hall and Molengraaff (1925). A high proportion of the width of the dikes and veins is commonly occupied by inclusions of the wallrocks, the pseudotachylyte in which they are embedded then being reduced to the role of cement. Although the inclusions have sometimes been shifted only an inch or two from the wall from which they were derived, "they are far more frequently rounded or turbinate than angular" (Shand, 1916, p. 205, and pl. 17, fig. 2), ranging from boulder-like forms a couple of feet in diameter down to minute grains.

Shand tentatively interpreted the veins and dikes of pseudotachylyte as a consequence of an "outrush of incandescent gases through all the fissures in the granite," while Hall and Molengraaff gained the "impression" that they resulted from "shattering . . . caused by some sort of omnilateral or static pressure." Fragmentation under conditions of omnilateral pressure, however, is only possible through the erosive power of a fluidized system, and the admixture of boulder-like forms and fine grains, indicating lack of elutriation, implies that the fluid concerned was gas. Indeed all the recorded phenomena are adequately accounted for as consequences of gas escaping along structural breaks within the granite. The initial fragmentation of the granite may even be a result of disaggregation implemented by through-flowing hot gas, for crystals of quartz and feldspar in the granite adjacent to the veins are cracked. Rock powder formed in this way would be fluidized by the rising gas streams which, in consequence, would become powerful agents of erosion capable of detaching blocks of granite from the walls of the channels, and of abrading them—as if by sandblast—into the rounded forms described by Shand as "reminiscent of a sedimentary conglomerate." In those examples where detached blocks of granite acquired boulder-like forms yet remained essentially in situ it can be inferred that the fluidized rock powder possessed the unique properties of the expanded bed, the density of which was of the right order to balance granite blocks. Veins and dikes formed in this way should be of non-dilation type, and in this connection it is of interest that Hall and Molengraaff (1925, fig. 15b, p. 105), in describing a particular vein, record that a "crystal of aegirine . . . cut by the pseudo-tachylyte was not split and thrust aside, but was partly taken up and replaced by the pseudo-tachylyte which became charged with specks of iron-ore."

That the gas had a high temperature is evidenced by the fact that feldspars derived from the granite and enclosed within the veins have actually been melted, the melted portions now showing structures attributable to viscous flow (Shand, 1916, p. 207 and pl. 18, fig. 1, pl. 19, fig. 2). By refractive index measurements, however, Waters and Campbell (1935) have shown that the matrix of the pseudotachylyte is not glass, a conclusion that Willemse (1936) has confirmed by means of X-ray powder photographs. It

is thus apparent that if the pseudotachylyte was fused it has since devitrified. Whether or not the pseudotachylyte originated as a gas-solid particle or a gas-liquid particle system, however, does not concern us here except in relation to Hall and Molengraaff's observation that some veins of pseudotachylyte have fine-grained selvages. These they regard as chilled edges of injected pseudotachylyte melt. In the absence of evidence of fusion, however, Waters and Campbell suggested that fine-grained selvages might conceivably develop as a consequence of difference in the rate of flowage of fragmented materials of slightly different granularity. This suggestion is verified by the observation that veins of glassy tuff near Kilchoan in Ardnamurchan have similar fine-grained selvages (see p. 591 and pl. 1-A). Fine-grained selvages could only be developed, however, if there was actual transport of the fragmented material, i.e. if the velocity of the gas streams was great enough, relative to the size of the fine-grained particles, to entrain them. That there was transport (as opposed to the turbulent motion of the expanded bed) of material within veins of pseudotachylyte with fine-grained selvages is evidenced by Hall and Molengraaff's observation that such veins "almost invariably carry inclusions of rock foreign to their encasing country-rock."

Recognition that some of the dikes and veins of pseudotachylyte in the Vredefort area exhibit expanded-bed phenomena, whereas others provide evidence of entrainment of their component materials, suggests that they were not all formed as a result of one single act. It suggests rather that they were formed through a period of time during which gas streams flowed along structural breaks to the surface with varying velocities and perhaps intermittently. One might even hazard a guess that the emplacement of dikes and veins of pseudotachylyte was represented at the surface by fissures of fumerole activity (correlatable with expanded-bed phenomena below the surface) and eruption (correlatable with entrainment of materials below the surface).

Enstatite-granophyre, Vredefort area.—To the north of the Vredefort granite, and striking approximately parallel to its margin, is a suite of dikes of enstatite-granophyre (Hall and Molengraaff, 1925, p. 56-62). These dikes intersect the granite, the surrounding sediments, and the younger intrusions of basic rocks. From the fact that no veins of pseudotachylyte have been found to cut the granophyre it can be inferred that the granophyre is either younger than or contemporaneous with the pseudotachylyte (Hall and Molengraaff, 1925, p. 111). From the further evidence that the rock near the extremity of an apophysis extending from a dike of enstatite-granophyre closely resembles some spherulitic varieties of pseudotachylyte, Hall and Molengraaff (1925, p. 62, 111-112) infer that the granophyre and pseudotachylyte are closely related in age and origin, the enstatite-granophyre possibly being —as they say—a "glorified" form of pseudotachylyte.

Hall and Molengraaff (1925, p. 56) record that the dikes of enstatite-granophyre are usually crowded with xenoliths derived from the rocks which they traverse, the proportion of xenoliths locally being so high that the dike has the appearance of a breccia. In many places xenoliths have been transported upwards from deeper levels, the source rock outcropping some distance away, and dipping toward the dike concerned. The enstatite-granophyre is

also related to the pseudotachylyte in its exceedingly fine-grained texture and in the presence of well-developed selvages of still finer grain. The latter Hall and Molengraaff (1925, p. 60) regard as chilled edges, but, as already recorded, their presence is equally to be expected if the granophyre dikes were emplaced as fluidized particles. Of paramount importance in deciphering the origin and mode of emplacement of the granophyre dikes, however, is the fact that they are not dilation dikes (Hall and Molengraaff, 1925, fig. 9, p. 57). They cannot therefore have been emplaced as magma. The map, figure 9,

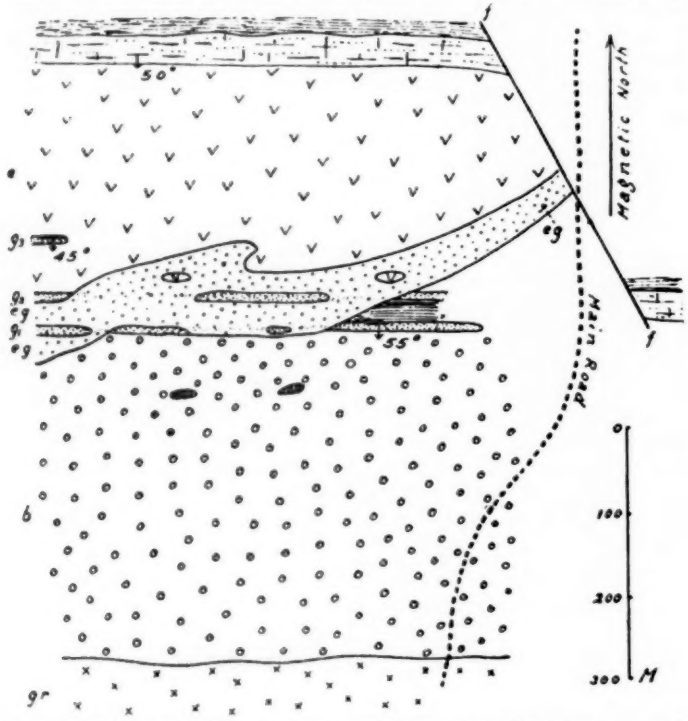


Fig. 2. Non-dilational dike of enstatite-granophyre (eg), Vredefort area, within and across which the pre-existing structure is traceable. gr = Vredefort granite, b = basal amygdaloid, $g_1 - g_3$ = Orange Grove quartzites, e = epidiorite. Reproduced from Hall and Molengraaff (1925, fig. 9, p. 57).

illustrating Hall and Molengraaff's Memoir, here reproduced as figure 2, shows that the depicted dike of granophyre has replaced vanished portions of the pre-existing country rocks, and that this replacement has been accomplished without any appreciable disturbance of the pre-existing structure which is clearly traceable across and within the dike. There are only two known ways in which such replacement can have been accomplished: either (1) the dike is a metasomatic replacement of the pre-existing rocks; or (2) it represents a route along which gas streams flowing to the surface gradually disaggregated, fluidized, and entrained portions of the rock framework they traversed.

The vanished parts of the rock framework may in this way have been transported upwards to the Earth's surface and outpoured, presumably from fissures, as tuff, ignimbrite or lava, dependent on the temperature of the gas concerned, and its physical relationship to the transported materials when the Earth's surface was reached. The place of rock thus removed would concomitantly be taken by fluidized materials from lower levels carried upwards by the gas streams. That the replacement dikes of granophyre were emplaced by process (2) and not by process (1) is evidenced by the facts (a) that they have fine-grained selvages against the country rocks, and (b) that xenoliths, transported upwards from lower levels, are present within the dikes.

The granophyre differs from the pseudotachylyte in one important respect: it has a relatively uniform chemical composition very little influenced by the composition of the immediately adjacent country rocks. This may possibly indicate that the enstatite-granophyre represents those fluidized particle streams within which mixing had most nearly attained perfection and chemical reaction between gas and particles had most nearly achieved equilibrium. As already noted on page 586, Fairbairn and Robson recognized that the matrices of the Sudbury breccias show convergence towards an igneous composition which they consider would have been the state of equilibrium, had there been time for its attainment.

It is of interest to refer here to a photograph, plate 12, and two drawings, figures 38 and 39, in Harker's Skye Memoir (1904). The photograph illustrates what Harker refers to as a tortuous flow structure in a dike characterized by "granophyre groups." This swirled flow structure is exactly what would be expected in the expanded bed phase of a fluidized system. The drawings, figures 38 and 39, illustrate the presence of undisturbed relics of basic layers (marscoite) within a younger intrusive granophyre. These drawings, which indicate that emplacement of the granophyre as liquid magma was mechanically impossible, resemble Hall and Molengraaff's illustration of the undisturbed relics of country rocks within intrusive enstatite-granophyre to which reference has just been made.

Intrusive granophyre, Slieve Gullion.—Further evidence concerning the origin of granophyre as a product of metasomatic transformation of intrusive ignimbrite emplaced as fluidized systems is found in the Slieve Gullion area, Northern Ireland (Reynolds, 1951b). Gently dipping layers of dolerite and acid rocks (lava flows and pyroclasts metamorphosed by volcanic heat) are transgressed by plug-like masses, veins and net veins of granophyre and related acid rocks. The observed facts (Reynolds, 1951b) relating to the transgressive granophyres are inconsistent with their having been emplaced as magma. Some of the masses and veins of granophyre occupy space where the layered rocks once existed, the vanished portions of which can commonly be reconstructed by reference to inclusions within the granophyres. Yet the transgressive granophyres are demonstrably intrusive since they contain relics of Caledonian granodiorite transported upwards from lower levels. They cannot therefore be explained as metasomatic replacements of the pre-existing layered rocks. They can, however, be adequately accounted for as products of metasomatic transformation of Caledonian granodiorite emplaced as fluidized

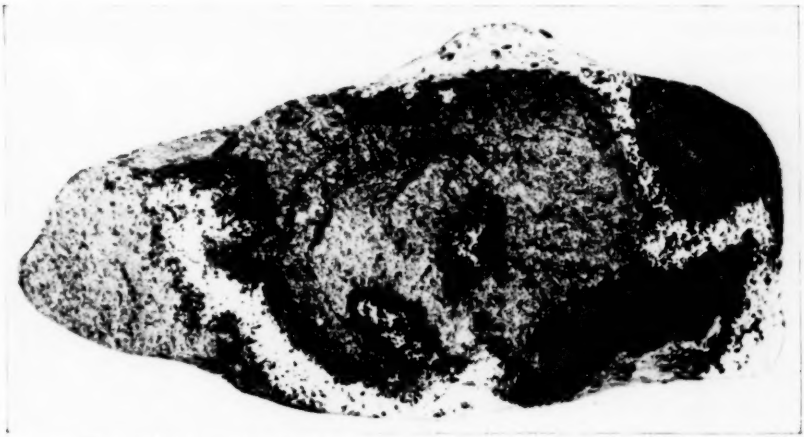
systems which, like the antecedents of the enstatite-granophyre of the Vredefort area, rose to the surface along faults and other structural breaks within the earlier rocks.

Not only is there abundant evidence in the Slieve Gullion area that the Tertiary acid rocks were evolved from Caledonian granodiorite (Reynolds, 1937, 1941, 1950, 1951b) but the chemical analyses of the various granophyres and related rocks form a variation diagram extending from the Caledonian granodiorite at the more basic end to Tertiary granophyre at the more acid end (Reynolds, 1951b, fig. 3, p. 107). The change in chemical composition from Caledonian granodiorite to Tertiary granophyre involved addition of Si and K to the granodiorite, and subtraction of Al, Ca, Fe, Mg, Na, Ti and P. As recorded in the earlier part of this paper, the importance of fluidized systems in industry is that they provide ideal conditions for chemical reaction between gas and solid particles. All that need be postulated in the Slieve Gullion area is that the added and subtracted materials diffused through the fluidizing gas.

Of outstanding significance in the Slieve Gullion area is the evidence (Reynolds, 1951b, 1952b) that narrow selvages of the doleritic layered rocks adjoining both the granophyre masses and veins have been melted (pl. 2-A). Not only is the material of these selvages exceedingly fine grained but the selvages, together with the granophyre veins and masses which they margin, transgress the lineations of the dolerites. The fine-grained selvages of the dolerites are thus related to the granophyres, and postdate the crystallization of the dolerites. Proof that they result from fusion of the dolerites is found where granophyre veins transgress dolerite characterized by phenocrysts of bytownite, An_{84}. The fine-grained dolerite edges then contain relics of bytownite dissected by stringers of pale glass such as result from partial melting. The refractive index of the glass is consistent with its having a composition, An_{53}, corresponding to that of the liquid which would form first if the bytownite were fused (Reynolds, 1952b). By reference to the thermal equilibrium diagram of the plagioclases (Bowen, 1913) the temperature at which liquid of composition An_{53} would form from the bytownite is 1458° C. at atmospheric pressure. It appears probable, however, that the melting took place at a water-vapor pressure of the order of 300 bars. The lowering of the fusion temperature of albite in the albite-water system at a vapor pressure of 300 bars is about 103° C. (Goranson, 1938). If the lowering of the fusion temperature of the bytownite concerned, in the presence of water vapor, is of the same order, then the partial fusion of the bytownite may be taken as indicating a minimum temperature of about 1355° C. At this temperature a high proportion of what is now the fine-grained margin of the dolerite would be melted. From the presence of shallow-tail plagioclases in many of the fine-grained edges it can be inferred that the melted material mainly solidified as glass which has since devitrified.

At a temperature of the order of 1355° C. much if not all of the granodiorite from which the granophyres were derived may be expected to have been melted, dependent on the length of time for which the high temperature was maintained. Within the transgressive granophyres under discussion

PLATE 2



A. Fine-grained margins (dark) due to melting and reconsolidation of dolerite (gray) adjacent to intrusive veins of granophyre (light). Slieve Gullion. .9 natural size. Reproduced from D. L. Reynolds (1951, pl. 1, fig. 3) by courtesy of the Council of the Royal Society of Edinburgh.

B. Non-dilational net veins of granophyre intruding dolerite, Slieve Gullion. The margins of the dolerite adjacent to granophyre veins are fine grained, as in plate 2-A, due to melting and reconsolidation of the dolerite.

crystals of zoned oligoclase form the only recognizable relics of the initial Caledonian granodiorite, and even these are traversed by stringers of pale glass indicative of partial melting (Reynolds, 1951b, 1952b). The collective evidence thus indicates that the transgressive granophyres were emplaced as fluidized systems in which the particles were molten (spray). When it first solidified, the antecedent material of the transgressive granophyres was therefore related to if not identical with ignimbrite, and it is from such glassy material that the transgressive granophyres are considered to have crystallized as a consequence of long-continued volcanic heat. That such glassy products should subsequently crystallize is not surprising in view of the evidence from the Valley of Ten Thousand Smokes referred to on p. 580. Moreover, Goranson (1932) found that granite-glass, made by melting Stone Mountain granite, became a mass of birefringent grains when subjected for 40 hours to a temperature of 600° C. at a water-vapor pressure of about 385 bars. Furthermore, in their recent experimental work on the alkali feldspars Bowen and Tuttle (1950) found it expedient to crystallize the feldspars from finely powdered glass of the appropriate composition. When the initial glass was ground very fine they obtained a very fine-grained completely crystalline product of uniform composition. On the other hand, large crystals grew when the glass was not ground to a very fine powder. There is thus an interdependence of the grain size of the initial glass particles and the subsequent crystalline product. As recorded above (p. 591 and pl. 1-A), net veins of ignimbrite near Kilchoan in Ardnamurchan have fine-grained edges. If these veins were to crystallize it may be expected that the difference in grain size of the edges and central part of the veins would be retained. This explains how it happens in the Slieve Gullion area that veins of granophyre, although emplaced as ignimbrite, sometimes have fine-grained edges.

Other evidence in the Slieve Gullion area that is of interest in the present connection is the presence of largely recrystallized mechanical hybrids occurring between the larger masses of transgressive granophyre and the doleritic layered rocks which they transgress (Reynolds, 1951b). Marscoite, for example, like the rock fragments ejected from Katmai and Montserrat, is characterized by a discordant assemblage of minerals, marscoite with its association of bytownite, quartz, and potash feldspar being a deeper-seated counterpart of the labradorite-dacites (bandaites) described by A. G. MacGregor (1938) from Montserrat. The chemical analyses of marscoite and of the adjacent dolerite and granophyre from the mixing of which it is derived form a straight line variation diagram (Reynolds, 1951b, fig. 4, p. 122).

FLUIDIZATION AND THE PROBLEM OF INTRUSIVE GRANITES

As a consequence of the application of Cloos' methods, the lineations within many granite[1] plutons (the massive granites of Hutton as distinct from the gneissic granites) have now been mapped. Two such recent investigations relate to granites respectively made famous by Rosenbusch and his opponent Michel Lévy, namely, the Barr-Andlau (de Waard, 1951) and the Flamanville (Martin, 1953) granites. The Barr-Andlau granite, according to Rosen-

[1] The term granite is used for brevity in this paper to include all the quartz-rich plutonic rocks.

busch, is a magmatic granite, while the Flamanville granite, according to Michel Lévy, is of metamorphic origin. The maps of both these plutons, like many earlier structural maps of granite plutons, indicate that the granites concerned show crosscutting, i.e. intrusive, relationships to the country rocks. It is equally clear from such structural maps, however, and this point is particularly well illustrated by de Waard's (1951) map of the Barr-Andlau pluton, that there is a space problem, since portions of the country rock framework now occupied by the granite are missing.

Difficulties of the magmatic stoping hypothesis.—Long before the idea of mapping the internal structural patterns of granite plutons had been thought of, Daly recognized that these bodies of rock replace vanished portions of the country rocks, and for nine years, he tells us, he was baffled as to how to explain the emplacement of these granite masses. Finally, guided by the breccias (intrusion breccias) that margin many of them, Daly was led to postulate that "acid batholithic magma has reached its present position in the earth's crust largely through the successive engulfment of suites of blocks broken out of the roof and walls of the batholith" (1912, p. 734). To this process he gave the name "magmatic stoping."

Daly describes the marginal breccias as consisting, when ideally developed, "of two concentric belts of mixed rock occurring between the homogeneous main body of igneous material and the encircling country-rock unaffected by any serious mechanical disturbance due to the intrusion. . . . The belt more remote from the intrusion is generally much the broader of the two, and consists of country-rock intersected by more or less numerous apophyses from the main igneous mass. The second belt is composed of igneous rock enclosing blocks of the country-rock. As the apophyses, breaking the continuity of the invaded formation, vary enormously in number within the outer belt, so the blocks, breaking the continuity of the igneous body, show the greatest variation in abundance. This belt of inclusions varies in width from a few feet to two miles or more. The blocks, unless very close together and possessing thoroughly massive structure themselves, usually show clear evidence of having been shifted out of their former relative positions in the invaded formation, so that their original orientation is completely lost. . . . Whatever be the causes of the disruption of blocks now found in the belt of inclusions, those causes are directly connected with the intrusive body itself. . . . The belt is, for example, not due in the normal case to the injection of magma into rock coarsely brecciated by regional dynamic movements in the earth's crust" (Daly, 1912, p. 727-728).

Since the country rocks generally have specific gravities higher than that appropriate to granite magma, Daly supposed that the loosened and disoriented blocks sank down through the magma. The all-over effect of the process of magmatic stoping is thus an exchange of place of materials: the country rocks sink, and granite magma rises. Gravity surveys of many granite plutons have now been made, however, and the results, both published (Thirlaway, 1951; Murphy, 1952; Cook and Murphy, 1952; Bean, 1953) and unpublished, show negative anomalies to be characteristic, i.e. there is a deficiency of mass where granite intrusions occur. This is inconsistent with the supposition that

they have been emplaced by down-stoping of the pre-existing rocks. Down-stoping involves no loss of mass, and the greatest effect on gravity measurements that exchange of place between granite and heavier country rocks could produce would be a relatively insignificant negative anomaly.[2] The results of gravity surveys thus indicate that the space now occupied by the granite was not provided by the down-sinking of the whole mass of pre-existing rock, but rather that a proportion at least of the pre-existing materials has vanished. Is it possible that the granite plutons providing evidence of stoping had direct communication with surface volcanoes or fumeroles whereby loss of mass could be accounted for? This is indeed strongly suggested by some structural maps, e.g. Flamanville (Martin, 1953), which show that part of the space now occupied by the granite was provided by shouldering aside of the country rocks adjoining the walls of the pluton. Such evidence implies that the country rocks forming the roof of the pluton have been stretched, thereby providing fractures which would form through-routes to the surface. Given such through-routes, and the necessity to erupt a proportion of the pre-existing materials with a density greater than that of granite in order to account for the present-day negative anomalies, it is difficult, if not impossible, to suppose that the granite was emplaced as liquid. The velocity of a liquid magma capable of upward transport of rock with a density greater than its own would be such that the magma would inevitably be erupted as lava flows having a volume of the same order as that of the space occupied by the granite mass concerned. As is well known, however, acid lavas are very far from being sufficiently voluminous to match this inference, to say nothing of the corresponding lack of inclusions or accidental pyroclasts.

There is, moreover, the mechanism of stoping to consider. Daly, in discussing the way in which magmatic stoping might be accomplished, made two suggestions. The first is that batholithic liquid is able to exert bursting pressure on the roof rocks, and thereby to shatter them. Daly himself, however, has emphasized the difficulty in understanding why a magma capable of such bursting pressure was not completely poured out as surface flows. This difficulty, in so far as liquid is concerned, is much enhanced by the more recent demonstration that the mobile antecedent of granite was capable of shouldering its walls apart, and in consequence stretching and weakening its roof. Daly's second suggestion is that the roof rocks of a granite batholith are shattered by differential heating. In reply to criticism of this suggestion by Richardson (1923) it was once again Daly himself who wrote: "Truly, the suggested brecciation of deeply covered country rock by slow, continuous, one-sided heating is a process less easily visualized than the breaking of rock by rapid changes of temperature at the earth's surface. Nevertheless, no better explanation of much of the contact shattering seems yet to have been published" (Daly, 1933, p. 275).

[2] Bott and Masson-Smith (Geol. Mag., 1953, v. 90, p. 127-130) have supposed that a negative Bouger anomaly over a granite mass, corresponding to a mass deficiency of $5 \sim 7 \times 10^{17}$ gm, can be explained as a consequence of down-stoping of heavier material. When this conclusion was questioned by Holmes (ibid., p. 222), however, they failed to substantiate their contention either in their reply (p. 223) or in a subsequent paper (ibid., p. 257-267).

Fluidization and stoping.—The discussion following the symposium on the "Origin of Granite" held at Ottawa in 1947 includes a very stimulating contribution by Sosman which is highly relevant to the present discussion. In his opening paragraph Sosman (1948) writes: "May a physical chemist speak on the term 'magma'? It seems to have been tacitly assumed in the preceding papers and discussion that a magma must be either a completely fused liquid or a liquid carrying some phenocrysts in suspension. I should like to introduce three facts to emphasize the possible fluidity of a magma consisting essentially of solid but freely movable particles or crystals." After reading the whole of Sosman's contribution it becomes evident that a fluidized system is the kind of magma he had in mind. It is questionable whether it is advisable to extend the term "magma" to include fluidized systems, but this is a matter for future decision. In any case a gas-particle system has quite different properties from basaltic lava. It differs from a lava in much the same way as a colloidal suspension differs from a solution. It is, moreover, able to erode and widen the structural breaks along which the fluidizing gas finds passageways to the surface, to isolate rock fragments and even large masses completely bounded by structural breaks, to transport particles of country rock to the surface, while larger masses remain behind as evidence of stoping. As high levels are reached, expanding gas is able to flow freely along minor fractures so that they in turn are eroded and widened; one characteristic consequence of this mechanism is the formation of net veins of replacement (non-dilational) type.

If some massive granites, like the granophyres already referred to, were to represent a former system of fluidized particles, then the marginal phenomena from which Daly inferred stoping would find a ready explanation. The marginal phenomena, including net veins and breccia zones, related to the emplacement of fluidized systems are depicted in the many excellent

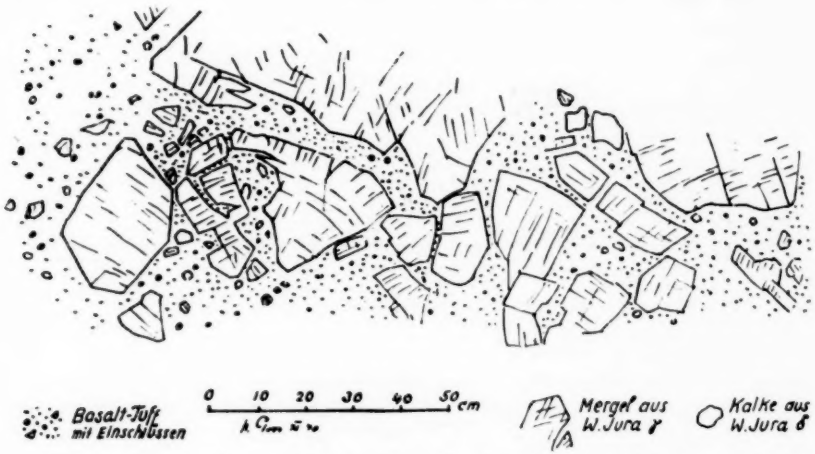


Fig. 3. Intrusion breccia formed by the invasion and stoping of Jurassic rocks by intrusive basalt-tuff. Reproduced from H. Cloos (1941, fig. 21, p. 741).

drawings illustrating Cloos' (1941) description of the Swabian tuff pipes (p. 584). Two of these drawings are here reproduced as figures 3 and 4. If the fluidized tuff in figure 3 were labeled granite this illustration might inadvertently be accepted as an illustration of magmatic stoping. There is clearly an urgent necessity for much more detailed investigation of the structures of marginal zones of plutons. If a particular pluton were emplaced as liquid magma, or as liquid charged with crystals, which made room for itself by stoping, be it down-stoping or up-stoping, then there must be clear evidence that the network of veins extending from its margin into the country rocks are all dilation veins, for this is the only way in which the stoped blocks could be separated by a liquid. If, on the other hand, the veins are commonly of replacement (non-dilation) type (Goodspeed, 1940; King, 1948), i.e. if part of their space was once occupied by now vanished country rock, then the evidence, though fatal to the hypothesis of stoping by a liquid magma, is entirely consistent with stoping by a fluidized system. It is truly ironical that Daly (1933, fig. 99, p. 271) illustrates magmatic stoping by a drawing of the roof contact of the Lausitz granite batholith in which the veins depicted are of replacement type (King, 1948, p. 474). In the areas with which the writer is most familiar, i.e. the Newry Complex (Reynolds, 1943) and the Slieve Gullion area (Reynolds, 1951b), both in Northern Ireland, replacement veins, plate 2-A, are the common type.

Replacement dikes and breccias of Cornucopia.—Probably the most detailed investigation of a marginal zone has been made by Goodspeed in the vicinity of Cornucopia, Oregon (1937, 1939, 1940, 1952, 1953). Here replacement dikes are characteristic, and the breccias have demonstrably been formed as a consequence of the intersection of replacement dikes and veins whose courses have in turn been controlled by joints or other structural breaks in the country rocks. Some of the replacement dikes and replacement breccias, however, show signs of flowage. This is evidenced by the alignment of elongated minerals within the replacement dikes and within the granitic or dioritic matrices of the breccias, and by the disorientation of relics of country rocks within the breccias. The examples showing such evidence of flowage Goodspeed refers to as "rheomorphic replacement dikes" and "rheomorphic replacement breccias." The term "rheomorphic" in accordance with its derivation means "flow form." It was introduced by Backlund (1937) to describe flowage of rocks where there is no evidence to show that the rocks concerned were melted and capable of liquid flow. Sederholm's term "palingenetic" already existed for describing new magmas generated by melting, and Backlund felt the need for an objective term implying flowage without hypothetical implications. From the flow forms of the dikes and breccias, and the presence within their flowed parts of newly formed euhedral crystals, Goodspeed infers that rheomorphism depended on the presence of intergranular fluid. Then substituting the word "liquid" for "fluid" he concludes that the flowed materials ranged from a mobile groutlike consistency to a more homogeneous liquid or even a melt. The writer fully appreciates how easy it is to slide down the slippery slope from "fluid" to "liquid" to "melt," having similarly fallen into error in describing the rocks margining the eastern end of the Newry

granodiorite (Reynolds, 1934, p. 595-596). From the presence of spectacular turbulent flow structures within marginal breccias of sedimentary origin it was inferred that the matrix of the breccias was liquid at the time of flowage and hence had melted. Further consideration resulted in the realization that fluidity did not necessarily imply the presence of liquid, and the descriptive term "mobilised sediments" (Reynolds, 1936a, p. 348, 355-358) was substituted for the original "fused sediments." It may be noted in passing, however, that the evidence relating to intrusive granite is of exactly the same kind; it is evidence of "fluidity" (in the most general sense, including mobility) and does not necessarily imply that the granite was once liquid.

Much of the evidence recorded from the Cornucopia area by Goodspeed is compatible with the rheomorphic materials having moved as fluidized systems. For example, one breccia (Goodspeed, 1953, p. 460-461) has a fragmental structure suggestive of cataclasis, yet its matrix shows flow structure around the fragments. Other breccias are characterized by vugs (Goodspeed, 1939, 1953) sometimes lined with minerals such as actinolite, limonitic material, white garnet, and feldspar. If the intergranular fluid was gas, as the vugs suggest, then the relationship between the "static" replacement dikes and breccias and their rheomorphic equivalents becomes understandable without invoking melting. Gas escaping along structural breaks would fluidize any loose particles, and erosion of the walls of the fractures would commence. If the velocity of gas flow relative to the size of the particles was such as to agitate without entraining them, as in the expanded bed of industry, then the fluidized systems would remain essentially in place and would gradually widen at the expense of the wallrocks. Replacement veins consisting of particles of the wallrocks agitated by the through-flowing gas would thus be formed. At the same time, at appropriate levels of temperature, the conditions would resemble those utilized in industrial processes in order to bring about chemical reaction between gas and solid particles, and metamorphism of the particles would be likely to occur. So long as the velocity of the gas was maintained the veins of turbulent particles would continue to widen by erosion of their walls, and by the intersection of such veins relatively large fragments of country rock would become isolated. The appearance at this stage, if the system became "frozen," would correspond to the "static" replacement breccias described by Goodspeed. With increase in the velocity of the gas the bubble phase would develop, bubbles traveling upwards through the turbulent vein material. If the system now became "frozen" these bubbles would appear as vugs. With still further increase in the velocity of the gas the particles within the veins would themselves become entrained and aligned by flowage. When the veins had become wide enough to appear as a matrix enclosing the fragments of country rock isolated by their intersection, there would be a particular velocity of gas flowage at which agitation and disorientation of the large fragments of country rock would commence. If the system now became "frozen" the appearances would correspond to those described by Goodspeed as "rheomorphic replacement breccias": the large fragments would be displaced and the matrix material would exhibit flow structure. In such a fluidized system the greatest chemical and mineralogical changes would be expected

in the finely fragmented matrix material; now, in fact, this material has a granodioritic or dioritic composition. Goodspeed (1953) describes the larger fragments as showing different degrees of transformation varying from a negligible change to complete recrystallization with either feldspathization or basification. If fluidization were the process concerned the chemical changes would be brought about by gaseous transport, silica and alkalis being added to the particles of the fluidized system while cafemic materials were extracted and carried away. Part of these subtracted materials Goodspeed (1937) has located in small-scale basic fronts where they have been fixed in the wall-rocks adjacent to granite bodies.

Reference to the Cornucopia area is not made with any specific desire to reinterpret the phenomena there displayed, but rather to illustrate—as can only be done by reference to a marginal zone where adequate observations have been made—the possibility that the fluidity of the antecedent of granite may have been that of fluidized particles rather than that of a liquid. One of the most difficult problems in geology is to discover in which direction to read evidence. The geologist who regards granite as having been emplaced as magma sees in the marginal phenomena the end stages of emplacement. It may be, however, as indicated above for Cornucopia, that marginal phenomena record the details of the initial progressive stages in the evolution of a granite mass.

Granite plutons.—Not only is stoping more readily understandable if the fluid antecedent of the granite is supposed to have been a fluidized system rather than a liquid melt but also many other observations concerning the granite of plutons become intelligible:

1. The negative gravity anomalies can be explained as due to actual loss of materials at the surface without facing the dilemma of having to explain how it comes about that the granite itself was not erupted. If the velocity of the gas was sufficient to fluidize the particles without entraining any of them, then loss of mass would depend entirely on the removal of cafemic materials by the gas. Apart from recognizable basic fronts (Reynolds, 1946), such materials might be dispersed into the air or deposited in some form at or near the surface, like the magnetite deposits of the Valley of Ten Thousand Smokes, whence they could since have been removed by denudation. There would, moreover, be a considerable range of gas velocities throughout which the fluidized system would remain essentially similar to the expanded bed of industry. As the velocity increased some of the particles would be transported upwards by the bubble phase and possibly be erupted at the surface. Only if the velocity of the gas were great enough to entrain the materials, however, would the maximum of extrusion occur.

2. The preservation within some granite plutons of undisturbed relics of pre-existing rocks, e.g. the basic dikes within the British Columbia granite (Phemister, 1945), can be explained even though the main mass of the granite was once mobile. Isolated blocks of country rock whose mass, relative to the velocity of the gas, was too great for them to become fluidized would remain in situ or slowly sink as though in quicksand. In either event their orientation would remain essentially undisturbed (fig. 1).

3. There is evidence from many granite plutons to show that the marginal zones represent granitized country rocks. If the granite originated as a fluidized system, there are at least two possibilities: (a) The granite might have derived its solid materials almost entirely from the fragmentation and fluidization of the adjacent country rocks, the conditions resembling those of the expanded bed (room for expansion would be provided by extrusion at the surface). In this event the marginal zone, in which fragmentation of the adjacent wallrocks would continue until the system "froze," would be likely to include transitional stages between country rock and granite, yet it might include fragments ("xenoliths") derived from a higher or lower level accordingly as their densities were greater or less than that of the expanded bed. The granite would be formed by transformation of the country rocks, and there would be no space problem, but fluidization of the materials would have given rise to new internal structures from the study of which the granite might be inferred to be intrusive. (b) If the velocity of the escaping gas was such that a high proportion of the fragmental material was entrained, the conditions would resemble those illustrated in figure 15, page 728 of Cloos' (1941) paper on the Swabian tuff pipes (see also fig. 4). There would be a central zone within which the bulk of the fragmented material would have risen from

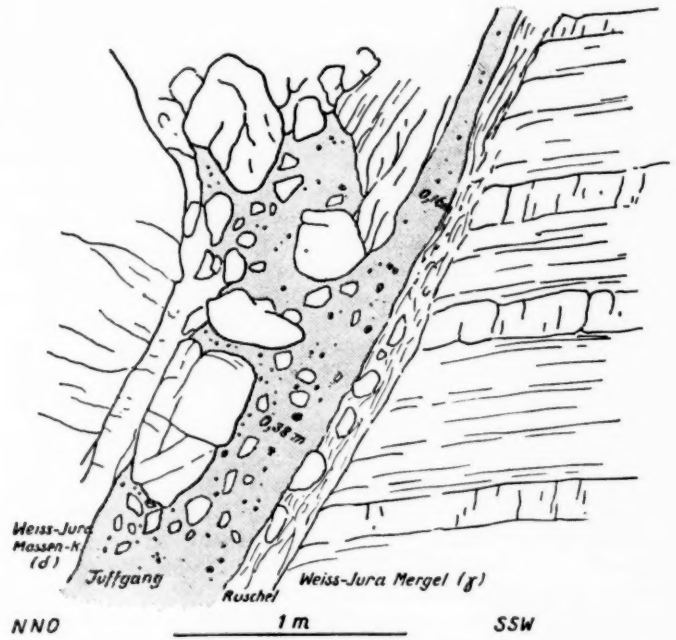


Fig. 4. Tuff dike composed of basalt lapilli and fine-grained fragments of Jurassic and Triassic rocks from lower horizons, together with larger fragments of the adjacent Jurassic rocks. The dike has a marginal zone of tuffisite formed by fragmentation of the adjacent Jurassic rocks. Reproduced from H. Cloos (1941, fig. 19, p. 738).

a lower level, and a marginal zone consisting largely of fragmented material derived from the adjacent wallrocks with some admixture of material from the central zone. A more or less sharp boundary between the two (or more) zones might be expected (Cloos, 1941, fig. 15, p. 728). As in (a) the marginal zone of the finally consolidated pluton would be likely to include transitional stages between the adjacent wallrock and the interior of the pluton. The marginal zone, moreover, representing a mixture (mechanical hybrid) of fragments derived from the wallrock with others from the central zone, would have a chemical composition intermediate between these two extremes, as occurs in some plutons. The space problem would be solved by upward transfer of an appropriate proportion of the rocks initially present, especially in the central zone of the pluton. This might result in extrusion at the surface, or in upward punching or dome-like raising of the roof, dependent on the velocity of the gas and the structural conditions of the roof which would jointly control the gas pressure.

4. The quartz (Keith and Tuttle, 1952), plagioclase, and alkali feldspar (Tuttle, 1952) of many granites, like those of paragneisses and schists, are low temperature forms. If these granites are crystalline derivatives of fluidized country rocks, it can be inferred that the temperature of the gas concerned was not high enough to fuse the fluidized particles, and that the recrystallization was a metamorphic process. Tuttle and Keith's assumption—based on the belief that all granites were emplaced as magmas—that the low temperature quartz and feldspar are inversions from high temperature varieties is not substantiated by the experimental experiences at the Geophysical Laboratory (Reynolds, 1952a, p. 242-248).

On the other hand the temperature of the gas which fluidized Caledonian granodiorite in the Slieve Gullion area, and thereby gave rise to intrusive Tertiary acid rocks, was high enough to fuse basalt, and it can be inferred that the particles in the fluidized antecedents of the acid rocks were molten droplets (p. 596). In their recent discovery that the quartz and feldspars of a Tertiary granite from Skye (unlike the corresponding minerals in granites previously investigated by them) are of high temperature type like those of rhyolite and quartz-porphyry, which are themselves high temperature products of the same process, Tuttle and Keith (1954) have supplied important corroborative evidence.

Intrusive breccias of Colonsay and Donegal.—Finally, reference may be made to two small plutons which, although not of granitic composition, provide evidence that some such process as fluidization was operative during their emplacement. The first of these intrusions, situated in Kiloran Bay in Colonsay, Inner Hebrides (Wright, 1911; Reynolds, 1936b), is elongated from east to west. Only its southern part is exposed, the northern margin being concealed beneath the sand of the bay. The exposed portion consists, in successive zones from north to south, of syenite, appinite, hornblendite (showing gradations to appinite throughout its mass), lamprophyre, and sedimentary breccia. At its outer margin where it adjoins the country rock phyllite, the breccia is formed almost completely of closely interlocking angular blocks of similar phyllite with a random orientation (Wright, 1911, pl. 5). As far as

can be seen within the limits of the exposures the contact of the breccia against the massive phyllite is steep, dipping outwards at an angle of about 60°. A few feet in from the margin, angular and occasionally rounded blocks of white quartzite, sometimes two feet or more across, are also present, together with rarer blocks of limestone. The latter is probably derived from the Colonsay limestone which margins and dips under the phyllite of Kiloran Bay. Away from the margin the proportion of quartzite blocks increases until the igneous contact is reached. There the breccia is composed almost completely of rounded and angular blocks, together with much larger masses of white quartzite. The latter, measurable in yards, are obviously representatives of a massive quartzite horizon. The blocks vary from a few inches up to 2 or 3 feet across, and the proportion of rounded to angular members increases greatly towards the igneous contact. No quartzite formation outcrops in the island, although similar quartzite occurs as small pebbles in conglomerate beds in the local succession, and also as xenoliths in some of the lamprophyre dikes. The facts indicate that the quartzite represents a formation older than the exposed country rocks. Whatever may have been the cause of the disruption of the blocks forming the breccia, it was related, as Daly (1912, p. 728) noted of marginal breccias in general, to the emplacement of the intrusion. It is equally evident from the disposition of the rock types within the breccia, the youngest variety occurring on the outer margin and the oldest on the inner, that it results from upheaval. The most surprising thing about the breccia, however, is the rounding of some of the quartzite blocks. So striking is this rounding that Wright (1911, p. 35) was led to regard them as water-worn boulders, derived from a loose surface formation, which had fallen into a fissure or pipe. Subsequently, having discovered that many of the boulder-like forms within the breccia have pink feldspathic rims, sometimes 2 or 3 inches broad, similar to those of xenolithic quartzite blocks within the hornblendite and appinite of the intrusion, the writer inferred that the rounding of the blocks was due to magmatic corrosion (Reynolds, 1936b, p. 371). It was at that time supposed that the hornblendite had crystallized from a magma with which the boulder-like forms in the breccia were at one time in direct contact. This hypothesis, however, leaves the occurrence of sparse rounded blocks of quartzite near the outer margin of the breccia without adequate explanation.

An intrusive breccia that is clearly related to and throws light on the origin of the Colonsay breccia has recently been described by Pitcher and Read (1952) from north of Glenties in Co. Donegal, Ireland. The marginal part of this intrusive breccia consists of a hornblendic rock charged with fragments of calc-silicate rock, derived from the immediately adjacent sedimentary series, together with a few fragments of quartzite. The middle of the intrusion, however, is composed of fragments of quartzite, in a scanty matrix, that have been transported upwards at least 1000 feet. The importance of this breccia is that some of the rounded quartzite fragments, which may be compared with "pebbles" in contrast with the "boulders" of Colonsay, have spindle and driekante shapes, and smooth striated surfaces such as result from sandblast. Referring to the significance of these pebble-like forms,

Pitcher and Read write: "They are clearly the result of the attrition of originally angular fragments in a moving medium of some kind. We may envisage a body of quartzite blocks, lubricated by a scanty medium, rushing violently thousands of feet up an opening pipe." Reference to the industrial process of fluidization provides a more adequate explanation for the abraded forms of the quartzite fragments. If the fluid medium were gas, its velocity need have been no greater than was necessary to expand the fragmented bed from which the quartzite blocks were derived in order to bring about their abrasion. This would be accomplished by agitation and turnover rather than by hurtling along. A subsequent increase in the velocity of the gas would entrain the quartzite blocks in the central zone of the pipe, and carry them to their present position where they would to some extent be mixed with the calc-silicate materials of the more slowly moving marginal zone (compare Cloos, 1941, fig. 15, p. 728).

A further point of interest is that the quartzite "pebbles" are all coated with a thin (maximum thickness 2-3 mm), dark-colored layer containing hornblende, biotite, chlorite and sphene, and a few of the calc-silicate rocks have similar dark-colored skins. These dark rims indicate that Al, Fe, Mg, Ti and OH, materials of basic front type, were transported upwards by the gas from lower levels. In this connection it may be recalled that Fairbairn and Robson similarly found the margins of fragments in the Sudbury breccias to be richer in hydroxyl-bearing minerals than the cores, and the matrices of the breccias to be richer in hydroxyl-bearing minerals than the fragments. Peters also records the presence of rims around the "boulders" of the Bull-Domingo breccia.

With regard to the matrices of the Donegal intrusive breccia, Pitcher and Read record: "There is an obvious relation between the nature of the matrix and the dominant xenolith. The granophyric matrix is associated with quartzite fragments and in it are relics of quartzite and of quartz grains; the appinite matrix is associated with calc-silicate fragments. We suggest that the two matrices are predominantly made of re-constituted quartzite and calc-silicate rocks respectively. This material has been comminuted in the pipe by the attrition of the fragments in the uprushing fluid and drenched and soaked by it." If for the idea of "drenched" and "soaked"—which inevitably suggest liquid, the elutriation effects of which are absent—that of chemical reaction between the solid particles and gas is substituted, then the phenomena are exactly what would be expected in a system of solid particles fluidized by gas.

It can be concluded that the quartzite and limestone of the Colonsay breccia were emplaced in a similar way. If in Colonsay, as in Donegal, it may also be supposed that the hornblendic rocks of the intrusion were derived from calc-silicate rocks, they must represent a calc-silicate horizon still older than the quartzite. Such a supposition makes it easier to understand how the hornblendite became charged with inclusions of quartzite in its upper part, and how these inclusions became rounded. If the rounding be attributed to magmatic corrosion, then the implied hornblendite magma, which would inevitably become enriched in silica in the process, must indeed have been

abnormally basic, for the hornblendite itself contains only 42 percent of silica (Reynolds, 1936b, table 2, no. 1, p. 394). It also becomes easier to understand how the interstices of the hornblendite became occupied by calcite, and how the rounded blocks of quartzite within the marginal breccia and hornblendite alike acquired pink feldspathic rims (micropegmatite and syenite), implying an addition to the quartzite of constituents in which the hornblendite itself is deficient. As already noted, the quartzite represents a horizon lower than any rocks exposed in Colonsay. Since the intrusion is located within the youngest rocks of the island, and the whole exposed succession has a thickness of the order of 5000 feet (Wright and Bailey, 1911, p. 18), the quartzite "boulders" must have been transported upwards a distance at least of this order, and the antecedent of the hornblendite must have traveled farther. The disorientation of blocks of the local phyllite at the outer margin of the breccia indicates that the velocity of the gas traveling along the structural breaks within the country rock phyllite adjacent to the intrusion was sufficient to expand this zone and fluidize the isolated blocks. With the cessation of gas flow these disoriented blocks of phyllite became compacted.

Marginal phenomena of Colville batholith.—The intrusive breccias of Colonsay and Donegal inevitably remind one of the remarkable marginal phenomena of the Colville batholith, Washington, described by Waters and Krauskopf (1941). The batholith intrudes and sharply transgresses folded sedimentary and volcanic rocks so that there is an obvious space problem which is intensified by Waters and Krauskopf's demonstration that the materials of the batholith have risen from a lower level largely in a solid state. For a breadth of a quarter of a mile or more the country rocks adjacent to the batholith have been made into a gigantic breccia which Waters and Krauskopf (1941, p. 1357) describe as follows: "Small faults penetrate everywhere, and along them movement has occurred resulting in the rotation of individual blocks with respect to one another so that the foliation and bedding near the contact are at all angles. Yet no great displacement of individual blocks has occurred, for in general a band of greenstone in the Anarchist series that trends into the contact will have a greenstone breccia at its end, and limestone masses end similarly in highly brecciated and mashed limestones which contain few foreign fragments." Comminuted material occurs between adjacent blocks in this breccia, and films and crusts of epidote and quartz occur along the faults and joints that subdivide the fragments. The marginal zone of the intrusion itself, which varies from a few yards up to 4 miles in width, consists of highly fragmented and foliated rock considered by Waters and Krauskopf to represent a migmatite that became mylonized and in extreme cases converted to pseudotachylyte as it was intruded to a higher level. They record, however, that the foliation in many ways bears a more marked resemblance to flow banding than it does to the foliation of metamorphic rocks. The outer zone of fragmental material passes gradually to an inner zone which, although still heterogeneous in character and providing evidence of fragmentation, is more uniform both structurally and petrographically than the outer zone. The remarkable thing about the inner zone is that over considerable areas the foliation "passes through the most involved convolutions and swirls"

(Waters and Krauskopf, p. 1384) in three dimensions, as though expressing turbulent flow. When traced eastward the plications of the swirled foliation gradually diminish, and at two localities within the mapped area they disappear entirely so that the batholithic rock becomes almost or quite structureless, and petrographically of the uniform character of granodiorite or quartz-diorite.

CONCLUSION

Fifty years ago Daly recognized that it is from the breccia zones of intrusions that their mode of emplacement is to be discovered. Although since then many such breccias have been uncritically accepted as indications of magmatic stoping, much new and significant evidence, some of which has been summarized in the preceding pages, has also been gleaned. By mapping the structures of breccias in the Swabian tuff pipes, Cloos has demonstrated that tuff, just as certainly as the granite or granodiorite of any pluton, has worked its way into position by both up-stoping and down-stoping, so that it can only be supposed to have been emplaced by escaping gas. In 1949, Dr. Oertel, who took part in the mapping of the Swabian tuff pipes, recognized from large hand specimens of breccia collected by the writer that the infilling of the vents associated with the Slieve Gullion ring dike were probably related in origin to those of the Swabian tuff pipes. On returning to the Slieve Gullion area, the writer not only became convinced that this was the correct interpretation of the vent materials but also reached the conclusion that the transgressive granophyres and associated breccias on Slieve Gullion itself are understandable only if it be supposed that the granophyres are metamorphic derivatives of flowing tuff derived by fragmentation from the underlying Caledonian granodiorite. Subsequently, at the close of a lecture on the Slieve Gullion area to the Geological Society of London, Dr. D. Whitten drew the writer's attention to the similarity between the process she envisaged as having been operative at Slieve Gullion and the industrial process of "fluidization." The writer is further indebted to Dr. Whitten for supplying her with references to investigations connected with the industrial process.

In this paper "fluidization" is established as a geological process; by a serial arrangement of geological examples of intrusive systems their specific characteristics are revealed; and, finally, the same characteristics are found to be represented amongst intrusive granites. Since a requisite for fluidization, on the scale of intrusive granites, is a large volume of through-flowing gas such as is known to escape at the surface only in volcanic regions, this implies that intrusive granites are likely to be subvolcanic phenomena. It is commonly tacitly assumed that large-scale intrusive granites were deeply buried and completely roofed—and not merely by their own volcanics—at the time of their emplacement. A perusal of the literature, however, reveals the fact that neither of these suppositions is well founded. On the other hand, many of the intrusive granites occurring in former volcanic regions have closely approached the surface, since they intrude lava flows and pyroclasts of the same epoch. One wonders whether it may not one day be possible to construct a denudation series extending from modern calderas through ring structures to the larger granite masses known as batholiths; and whether it may not be

possible to trace a continuous series of metamorphic changes in down-sunken volcanic rocks (especially the more easily recognized andesitic and basaltic types) from lavas such as those of Glen Coe and the Ossipee area, through highly metamorphosed volcanics like those of Slieve Gullion (where the basic lavas were originally mistaken for subvolcanic gabbro) to the more coarsely crystalline basic rocks associated with the larger granites. It may be that intrusive granites did not come into being by a single act—such as intrusion of magma—but rather that each developed as the eventual consequence of a long succession of acts which spanned the whole life of a volcano. Granite complexes may be palimpsests from which the histories of long-vanished volcanoes may yet be read, using the associated basic masses as guides, just as Sederholm deciphered the story of successive orogenic phases from Precambrian gneisses with the aid of their retinues of basic dikes.

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GLAUCOPHANE SCHISTS FROM THE NORTH BERKELEY HILLS, CALIFORNIA

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ABSTRACT. Scattered blocks and tors of glaucophane schist in the North Berkeley Hills are tectonic inclusions in a belt of serpentinite emplaced along a fault zone in Franciscan-Knoxville rocks. Associated with the schists are eclogites, garnet-amphibole and epidote-amphibole rocks, and low-grade albite-epidote-muscovite-chlorite schists; all of these rocks show incipient replacement by glaucophane. The mineralogy of each group of rocks is described. It is not clear if the two processes are related, but both serpentinization of the original peridotite and recrystallization of the glaucophane rocks occurred mainly at depth prior to intrusion of the serpentinite as an essentially solid body. Late-stage metasomatism during injection of the serpentinite was responsible for the growth of glaucophane in small amounts in adjacent Franciscan-Knoxville sediments. Formation of the various glaucophane assemblages from their parent rocks is believed due to a number of lines of descent under different conditions of metamorphism.

INTRODUCTION

Outcrops of glaucophane schists in the Coast Ranges of California have attracted the attention of geologists for many years, and a number of studies have been made of their field relationships, structure, and mineralogy. Taliaferro (1943) reviewed the literature on the subject and gave an account of the regional distribution of the schists, their characteristics, and probable mode of origin by metasomatism associated with ultrabasic intrusions. During the last ten years Switzer (1945; 1951), Turner (1947a), Travis (1950), Turner and Verhoogen (1951), Crittenden (1951), and Borg (1954) have contributed to the topic. In California the glaucophane schists and allied metamorphic rocks are associated with the Upper Jurassic Franciscan-Knoxville Group, a varied set of rocks including indurated sandstones, argillites, cherts, basic igneous rocks, and intruded masses of serpentinized peridotite. At a number of places, the schists are in close proximity to the serpentinite; but in others the relationship is not clear because of a tendency for the more resistant schists to remain as fallen blocks on the land surface during lowering of relief. Structural studies of the glaucophane rocks in many districts are therefore of doubtful value, for not only may the outcrops be shifted erosion-residuals, but even large masses that appear to be in place may possibly be tectonic inclusions in serpentinite. Nevertheless, in all described Californian localities there is remarkable uniformity in the mineralogy of the completely recrystallized glaucophane schists and of those rocks that have been partially converted to the glaucophane-bearing assemblage.

Parts of the North Berkeley Hills were reported on in several geology theses presented in the University of California between 1900 and 1925 (Stenger and Theller, 1907; McMillan and Waldner, 1914), but no modern petrographic study of the numerous outcrops of glaucophane schist has been made. The growing popularity of the Hills as a residential district has made accessible in road cuttings and excavations more exposures than were available in the past. However, many smaller outcrops of schists are being concealed by new buildings or will soon be destroyed as the district becomes more developed. In the present survey 58 areas of glaucophane schist and associated metamorphic rocks have been located on an outcrop map which covers the

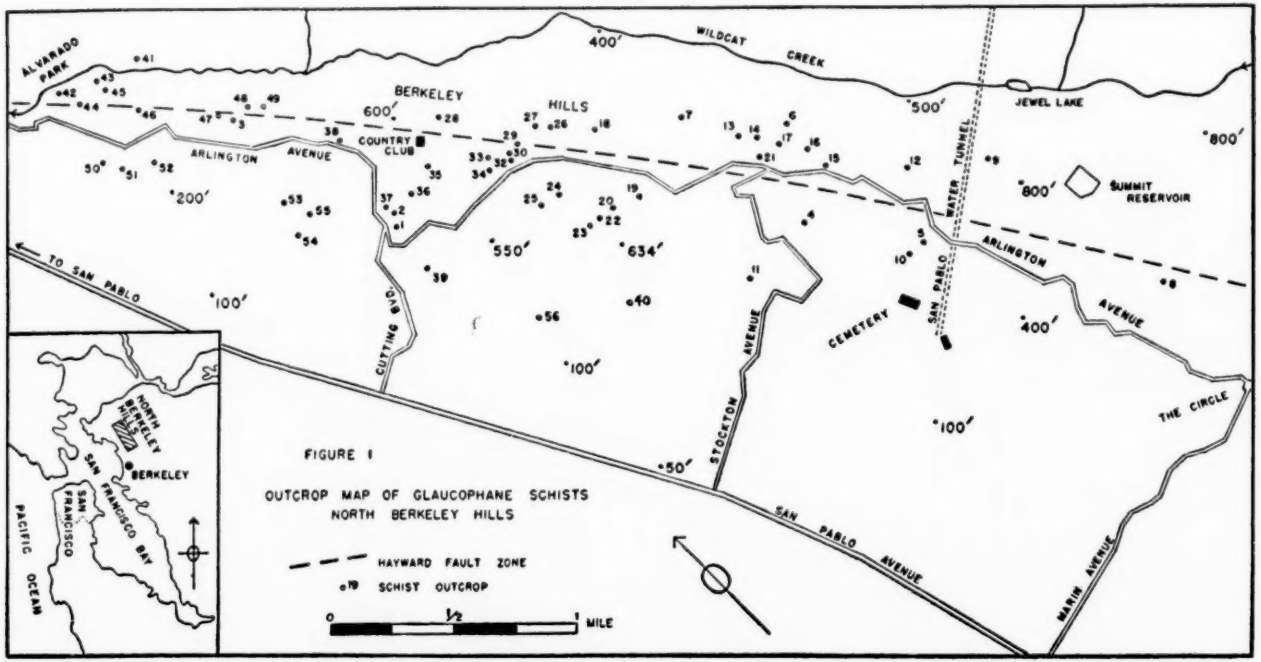

FIGURE 1

OUTCROP MAP OF GLAUCOPHANE SCHISTS
NORTH BERKELEY HILLS

hills from near the University campus northwest to Alvarado Park (fig. 1). Hand specimens and thin sections of these rocks, together with field sheets, have been filed in the petrology collection at the Department of Geological Sciences, Berkeley, and a duplicate set of specimens is available at the Geology Department, Auckland University College, New Zealand. In the following text, reference is made to these specimens by numbers and number-letter combinations, given in parentheses.

GEOLOGIC SETTING

The North Berkeley Hills run parallel to the eastern shore of San Francisco Bay and gradually decrease in height northwestward from about 1000 feet at Berkeley to 200 feet near San Pablo. The eastern edge of the hills is marked by the steep western valley wall of Wildcat Creek (fig. 1), but to the west more gentle slopes descend to the alluvial flats along the margins of the Bay. The crestline is therefore asymmetrical and its position is indicated roughly by Arlington Avenue, the main road along the hills. West of Arlington Avenue rocks of the Franciscan-Knoxville Group outcrop on the hill slopes as indurated sandstones and argillites with a general NW-SE strike. The crestline is occupied by an elongated body of sheared serpentinite and silica-carbonate rock which makes very few surface features but can be traced along the length of the hills. Occasional large rounded tors of glaucophane-bearing rocks, as much as 50 feet high and 40 feet across, stand above the serpentinite and many smaller blocks of schist lie on its surface. In some places, as near Cutting Boulevard, fallen blocks of schist have traveled some distance down the western slope of the hills and lie upon Franciscan-Knoxville rocks, but none have been seen embedded in or passing directly into these sediments. East of the crest to the valley of Wildcat Creek soft sands, gravels and clays of the Orinda Formation (Upper Tertiary) form a steep scarp along the edge of the Hayward fault zone. The inferred position of the fault zone, coinciding approximately with the intruded serpentinite mass, is shown in figure 1.

A geological section compiled during the excavation of the San Pablo water tunnel in 1906 has been kindly made available by Dr. G. D. Louderback and is given in figure 2. The section shows quite clearly that the serpentinite is located within a zone of dislocation and shearing, and more importantly that all glaucophane schists encountered in the tunnel are included within the serpentinite body or very closely associated with it. The structural interpretation drawn in figure 2 is that of the original section. The identity of the schists as large tectonic inclusions in the serpentinite was confirmed by analysis of macroscopic structural elements in 33 outcrops, selected in the field for their obvious location in the serpentinite belt. Many of these schists, especially the finer-grained ones, possess a well-defined fold axis and one or more lineations. Projections of poles to foliation planes and of lineations gave scatter diagrams in which no structural unity could be detected. Random orientation of the rocks was evident even when a detailed analysis was made of three strongly foliated tors 100 yards apart. The schist outcrops therefore cannot be regarded as inliers of one large mass seated in the serpentinite, but rather

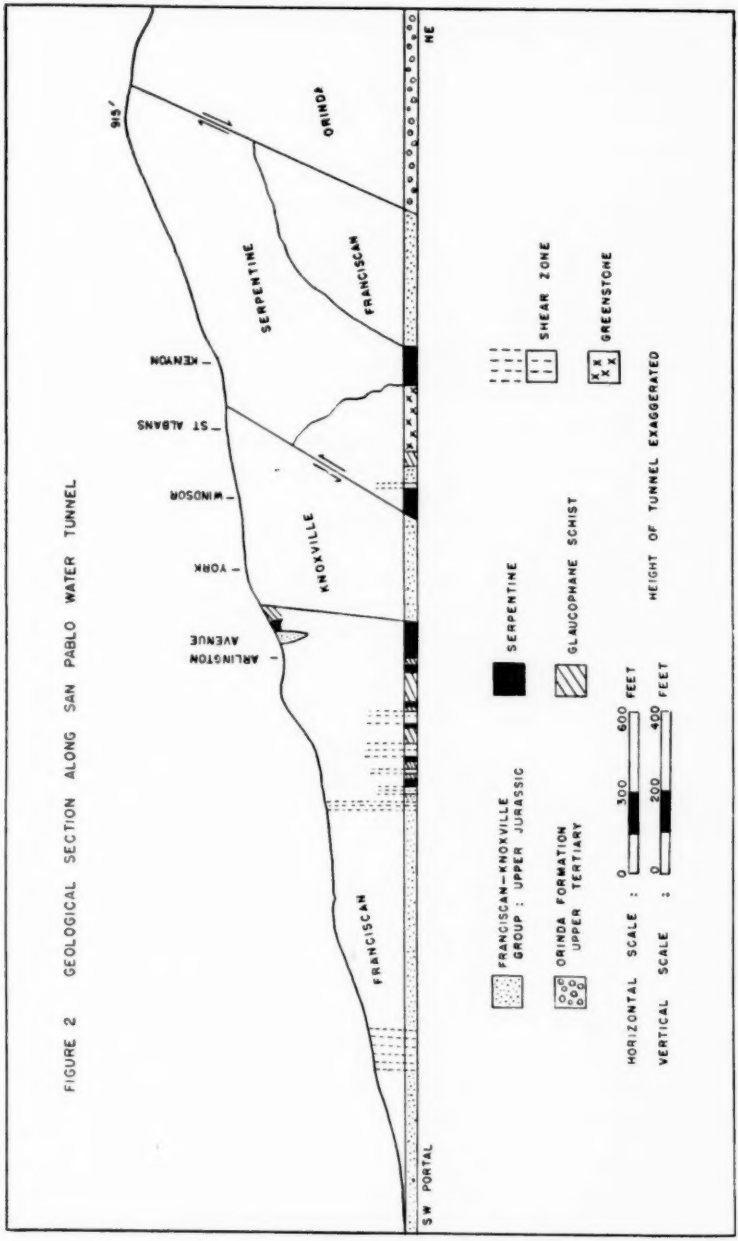
FIGURE 2 GEOLOGICAL SECTION ALONG SAN PABLO WATER TUNNEL
SW PORTAL
FRANCISCAN
ARLINGTON AVENUE
YORK
WINDSOR
ST ALBANS
KENYON
KNOXVILLE
SERPENTINE
FRANCISCAN
ORINDA
NE
FRANCISCAN–KNOXVILLE GROUP : UPPER JURASSIC
ORINDA FORMATION UPPER TERTIARY
SERPENTINE
GLAUCOPHANE SCHIST
SHEAR ZONE
GREENSTONE
HORIZONTAL SCALE : 0 300 600 FEET
VERTICAL SCALE : 0 200 400 FEET
HEIGHT OF TUNNEL EXAGGERATED

as fragments of irregular size floating in the altered ultrabasic rock. In addition to structural evidence this view is supported by rapid haphazard variation in rock type in adjacent outcrops. Nowhere was a clear contact seen between the serpentinite and the Franciscan-Knoxville rocks. It is important to note, however, that where the two are in close proximity occasionally small crystals of glaucophane have developed in the otherwise unmetamorphosed sediments (e.g. 22).

SUMMARY OF MINERALOGY

In general, three main types of metamorphic rock have been recognized in the North Berkeley area:

(a) Glaucophane- or tremolite-bearing schists in which lawsonite, pumpellyite, epidote, and clinozoisite assume importance in varying amounts as accessory or even as dominant minerals. Muscovite, chlorite, quartz, albite, and sphene appear in this group of rocks, and relict garnet and pyroxene are common in small quantities. In some cases quartz, or albite and quartz, occur in quantity, the former usually in glaucophane schists and the latter in stilpnomelane-crossite rocks.

(b) Rocks in which mineral assemblages typical of the greenschist facies are present, such as albite-epidote-muscovite-chlorite. Rarely a minor amount of glaucophane may be present.

(c) Rocks rich in pyroxene and/or amphibole, and containing in addition important amounts of epidote and garnet; accessory glaucophane and lawsonite are sometimes present. The amphibole is usually blue-green hornblende but the pyroxene varies in composition from diopside-acmite to jadeite.

In a list of rock types given later the above three divisions are expanded into eight groups with contrasted mineralogy. The following descriptive notes apply to the principal minerals upon which this grouping is based. Optical and crystallographic data have been determined with a universal stage.

Lawsonite.—Lawsonite is an essential mineral in many of the glaucophane schists, in some (1m) making up 40 percent of the total rock. It is not confined to veins in the schists but forms strong folia usually alternating with glaucophane-rich layers. Larger crystals poikiloblastically enclose glaucophane, muscovite, sphene, and clinozoisite. The crystals are usually long and tabular, flattened parallel to {001} which is also the only well-developed bounding face; large porphyroblasts typically contain strings of dust-like inclusions. Completely euhedral crystals are best developed where lawsonite is associated with muscovite, and in these domes {0kl} form prominent faces together with {110} and {111}. The strongest cleavage is parallel to {010}, and this feature helps to distinguish lawsonite easily from the epidote group. Polysynthetic twinning parallel to faces of the unit prism is fairly common, single crystals often showing intersecting lamellae belonging to {110} and {1$\bar{1}$0} twins (with X = *a*, Y = *b*, Z = *c*). The optic axial angle about Z is variable from 73° to 89° and most often lies between 84° and 88°. Where lawsonite is poorly crystallized in small patches it strongly resembles prehnite, from which it can be distinguished by the cleavage angle, X$\wedge${110} = 34°.

Replacement of garnet by lawsonite is not uncommon (3a, 4n, 54d) and in one case (20b) seven crystals grouped about a deeply embayed garnet

showed a high degree of preferred orientation. Association of lawsonite with epidote or clinozoisite, while not usual, has been noted in a number of slides (e.g. 4k, 20c, 52, 54d), and in (25), a chlorite-muscovite-clinozoisite-lawsonite schist, prophyroblasts of lawsonite enclose small well-formed crystals of clinozoisite. Lawsonite may be partially replaced by pumpellyite or rarely by calcite (49).

Pumpellyite.—In most cases pumpellyite is associated with lawsonite, especially where the latter forms strong folia. Pumpellyite may be intergrown with lawsonite either as broad laminae with the plane of contact {001} of lawsonite, or as elongated serrated crystals similar to those described by Coombs (1953) as "oak-leaf twins." Elsewhere pumpellyite appears to replace lawsonite, the absence of a sharp contact and the contrasting pleochroism and birefringence making the replacement conspicuous. Pumpellyite appears in quantity in some rocks lacking lawsonite, as patches in (51), as vein material (4j), or as large crystals tabular parallel to {100} and elongated parallel to Y. In only one specimen (39) some crystals are tabular parallel to {010}. In a glaucophane-pumpellyite-muscovite schist (38b) crystals measuring up to 2.3 mm by 0.34 mm make up 40 percent of the rock in heavy bands containing twins with {100} as composition planes. Together with epidote, lawsonite, or chlorite, crystals of pumpellyite often cluster around relict garnets (4n) and may penetrate garnet along fractures (20c). The optic axial plane is always parallel to {010}; $2V_Z$ usually lies between 16° and 38° but more rarely between 54° and 68°. Dispersion of the optic axes is very strong with $r<v$; pleochroism is fairly constant with X and Z = colorless and Y = pale to bright green.

Epidote and clinozoisite.—Pale green or colorless epidote is far more common than clinozoisite in all three groups of rocks noted above, although in one specimen (41d) the two minerals are subequal in amount and together make up 60 percent of an epidote-amphibole rock. Both are typically granular in appearance except in some garnet-hornblende and pyroxene rocks (11e, 32, 32b) where large euhedral epidotes are elongated parallel to Y with strong {001} cleavage. In these rocks epidote also shows zoning and polysynthetic and simple twins on {100}. The breakdown of relict garnets in the glaucophane schists is often accompanied by development of the new association epidote-pumpellyite-muscovite.

Glaucophane.—Glaucophane is the most ubiquitous mineral in the North Berkeley rocks. Apart from being the index mineral in a large group of lawsonite-epidote-muscovite-pumpellyite-chlorite schists, it appears in minor quantity in a number of different settings. In (56d) a pyroxene-epidote rock, and in (39b) a lawsonite-jadeite rock, it occurs in long thin interstitial patches. In (32b, 32d, 41a, 42) it is clearly replacing blue-green hornblende, while in (56g) an epidote-amphibole rock, it has almost completely pseudomorphed the hornblende in many crystals; in these replacements the two minerals share a common Y axis of the indicatrix = [010]. Other rocks which have the appearance of being metamorphosed sediments (22, 19) contain glaucophane throughout as a fine-grained mesh, and in (47a) a lawsonite-chlorite schist, it is present as needle-like crystals associated with chlorite along small shear

planes. Similarly albite-epidote-muscovite-chlorite rocks (11f) which otherwise appear to be typical greenschists have small amounts of ragged and thin glaucophane crystals. Franciscan-Knoxville tuffs near the contact with the serpentinite contain what seems to be metasomatically introduced glaucophane.

Where in quantity, glaucophane is subhedral and occurs as either short stumpy laths or crystals elongated parallel to the foliation of the rock. The range of pleochroism varies from very pale colors to strong pastel shades, presumably as the tenor of iron changes, but this variation cannot be correlated with variation in occurrence or associates. A typical pleochroic scheme is X = colorless, Y = lavender blue, Z = sky blue. Optical properties are uniform with $2V_X = 30°\text{-}72°$ and $Z\wedge c = 4°\text{-}10°$.

Crossite.—Long fibrous clusters of crossite seated in quartz and albite appear in six specimens. The characteristic pleochroism with X = yellowish, Y = blue-green and Z = violet, the extreme dispersion of optic axes and bisectrices giving incomplete extinction, and the orientation of the optic axial plane normal to the cleavage serve to distinguish crossite from other amphiboles in the North Berkeley rocks. The type specimen of crossite, described by Palache (1894), was found in the North Berkeley Hills; it is specimen (307-8) of this paper.

Tremolite-actinolite.—Where it is present in the schists, tremolite-actinolite occurs in large amounts up to 90 percent of the rock as long thin crystals with very faint pleochroism. In (13c) it shows more body color with X = colorless, Y = pale yellowish green and Z = light blue-green. The ends of some crystals are intensely pleochroic, resembling glaucophane; but otherwise these two minerals have not been seen together in any sections. $2V_X$ ranges from 79° to 86° with occasional values as low as 74°; $Z\wedge c = 13°\text{-}18°$.

Hornblende.—A blue-green hornblende, with a consistent pleochroic scheme, X = yellowish green, Y = olive-green, Z = blue-green, appears in large quantities in garnet- and epidote-amphibole rocks (32b, 56g) and as residuals of larger grains replaced by glaucophane in glaucophane-epidote-muscovite-chlorite schists. In (209-9) large crystals of hornblende, with X = colorless, Y = pale green to pale blue and Z = pale blue-green, are porphyroblastic in chlorite schist. $2V_X = 62°\text{-}84°$, and $Z\wedge c = 10°\text{-}22°$.

Pyroxenes.—A weakly colored pyroxene, with X = green, Y = pale green and Z = yellow, is present in minor amounts in the glaucophane schists and in the epidote- and garnet-hornblende rocks. In some amphibole rocks and many of the schists the pyroxene is in small ragged grains coated with iron oxide or showing replacement by chlorite (43a), and the mineral is obviously unstable in the accompanying assemblage. In other schists (50) the pyroxene is fresh and clear and forms thick bands. The same mineral constitutes the bulk of the pyroxene-rich eclogitic rocks in which it is associated with garnet and epidote. The optic axial angle lies between 58° and 88° (+), $Z\wedge c = 46°\text{-}64°$, dispersion $r>v$ is moderate, and birefringence is about .015. The pyroxene therefore belongs to the diopside-acmite series, and on the average contains about 40 percent of the acmite molecule. A few slides (32, 46) contain a pale green variety nearer the acmite end of the series with $2V_X = 88°$ and $Z\wedge c = 60°\text{-}64°$; extinction is incomplete in anomalous blues

and browns. Colorless jadeite with strong dispersion ($r>v$) and lower birefringence forms the bulk of (39b), a lawsonite-jadeite-glaucophane rock. A diopsidic pyroxene with $2V_Z = 60°$, $Z\wedge c = 37°$ is associated with tremolite-actinolite as small granules spread out along schistosity planes between larger crystals of the amphibole (42f).

Garnet.—Relict grains of pink almandine are common in the glaucophane schists, and occur as large fractured euhedra with grain size well above that of the enclosing rock. These crystals are sometimes almost completely pseudomorphed by chlorite, but more often are in various stages of replacement by chlorite (32) and muscovite (42d) at their centers, and by epidote (32b), lawsonite, and pumpellyite (20b, 54d) at the edges. Original inclusions in the garnets are small deeply colored rods of rutile. In quartz-glaucophane schists (4a, 4b) the garnet is fresh and clear in small {110} euhedra enclosing patches of quartz. Garnets similar to those in the schists occur in large quantity in the hornblende-garnet and pyroxene-garnet rocks.

Albite.—Albite is never present in large amounts in the glaucophane-bearing schists where it is confined to small interstitial patches (17), to quartz lenses (11d) or to the quartz-calcite veins which are seen rarely in these rocks (27a). In the assemblages quartz-stilpnomelane-crossite (209-4) and epidote-muscovite-chlorite (50) albite often appears in quantity and may contribute as much as 70 percent to the bulk composition of the rocks. Usually the feldspar is not twinned, but occasional carlsbad and albite twins enable the composition to be fixed between An_0 and An_4, using Turner's (1947b) curves. According to the data of Tuttle and Bowen (1950) the albite is the low-temperature form, with $2V_Z = 68°$-$79°$.

ROCK TYPES

Altogether eight distinctive groups of rocks have been recognized in the North Berkeley metamorphics and these embrace 36 mineral assemblages:

(1) lawsonite-pumpellyite-muscovite-glaucophane (32, 20c)
lawsonite-muscovite-glaucophane (4m, 52d)
lawsonite-pumpellyite-glaucophane (20b)
lawsonite-glaucophane (17, 49)
lawsonite-chlorite-glaucophane (47a)
lawsonite-muscovite-epidote-glaucophane (4k, 52)
epidote-pumpellyite-glaucophane (38c, 39)
epidote-muscovite-glaucophane (11d, 27a)
epidote-chlorite-glaucophane (46)
pumpellyite-muscovite-glaucophane (38b, 45)
muscovite-chlorite-glaucophane (32c)
chlorite-sphene-glaucophane (32e)

Members of this group are the most abundant in outcrops and usually they possess a strong foliation and at least one lineation. Grain size is uniformly medium to coarse, and apart from rare veins of quartz and calcite there is a complete absence of fissure fillings. Quartz and albite appear interstitially in a few schists. Sphene is almost always a minor constituent as either clusters of granules, or large wedge-shaped crystals spread out along schistosity

planes. Coarse grains of apatite and small rods of hematite and rutile have been noted as well as consistently small amounts of relict garnet and pyroxene.

(2) quartz-garnet-glaucophane (4a)
quartz-muscovite-glaucophane (4b, 4g)
quartz-lawsonite-glaucophane (18)
quartz-muscovite-stilpnomelane-glaucophane (58)

The quartz-glaucophane schists are outstanding for their lack of albite, and for the presence of unaltered crystals of newly generated garnet. Apatite, sphene, and epidote are accessory. Stilpnomelane forms clumps of radiating crystals usually associated with muscovite.

(3) glaucophane-albite (28c)
glaucophane-sericitic mica (19)

(28c) is essentially a bimineralic rock with coarse crystals of glaucophane and albite in a ratio of 4:1 and accessory sphene; cross-cutting veins contain albite and calcite. (19) has an extremely fine grain size but is strongly foliated, so that the glaucophane and the mica show extinction effects parallel to the folia; epidote is a minor constitutent.

(4) quartz-albite-crossite (209-3, 307-8, 307-10)
quartz-albite-stilpnomelane (329-93)
quartz-albite-stilpnomelane-garnet-crossite (209-4, 329-85)

These rocks were not collected by the writer but were examined from the petrology collection at the Department of Geological Sciences, Berkeley. They represent outcrops sampled in the North Berkeley Hills by earlier workers and, as decided by Palache (1894) for his specimen (307-8), are considered to have been in place. In all specimens albite lenses are numerous, and optically continuous patches enclose quartz and stilpnomelane. Stilpnomelane forms large radiating crystals often intergrown at their intersection with small amounts of sphene and opaque ore. Unaltered colorless euhedra of garnet are scattered throughout (209-4, 329-85).

(5) tremolite-actinolite (4h, 13c, 17b)
tremolite-actinolite-lawsonite-quartz-chlorite (4)
tremolite-actinolite-albite-epidote (24c)

Tremolite-actinolite rocks are restricted in occurrence to two settings. The first is as nodules up to 8 inches in diameter composed almost entirely of the amphibole with accessory sphene and apatite. The nodules are contained by the serpentinite along Arlington Avenue and in them tremolite-actinolite forms long radially disposed crystals. The second mode of occurrence is as heavy coatings 2 to 3 inches thick on outcrops of glaucophane schists; but no tremolite-actinolite layers have been seen within the masses of glaucophane rocks. In this situation, e.g. outcrop (17), the amphibole crystals may appear in rosettes as much as 3 inches in diameter and may be accompanied by varying amounts of muscovite and lawsonite (17b).

(6) quartz-albite-sericitic mica (40)
albite-epidote-muscovite-chlorite (11f, 48)
muscovite-epidote (3e)
albite-clinozoisite-muscovite-chlorite (47b)
chlorite-muscovite or epidote (3c, 51a, 209-9)
chlorite-muscovite-clinozoisite (25)

This group of schists differs from others by possessing a very weak foliation and by containing a low-grade assemblage of minerals of irregular grain size. However, the presence of a few ragged glaucophane crystals in (11f) and small grains of garnet (3e), soda-pyroxene (47b), lawsonite (25) and hornblende (209-9) set these rocks slightly apart from typical greenschists.

(7) epidote-hornblende (41a, 41d, 56h)
chlorite-hornblende (42)
garnet-hornblende (32b, 32d, 57)

In all specimens the blue-green hornblende has been partially replaced by glaucophane. Relict grains of iron-coated soda-pyroxene appear in most sections and in (56g) are surrounded and replaced by hornblende. Large euhedral garnets, clearly unstable in the epidote-amphibole rocks, show conversion to epidote, stilpnomelane, and chlorite (56g). Sphene, muscovite, chlorite, apatite, and opaque ore are minor constituents.

(8) epidote-pyroxene (56d, 11e)
lawsonite-jadeite-glaucophane (39b)
garnet-pyroxene (32)

A number of accessory minerals accompany the garnet-pyroxene assemblage (32) and constitute about 40 percent of the rock. Blue-green hornblende and chlorite together form rough laminae so that the amphibole is never seen in direct contact with the soda-pyroxene. Small patches of glaucophane replace the hornblende and in some places have grown along fractures in the pyroxene. Coarse crystals of apatite, sphene, epidote, and muscovite are associated with the hornblende-chlorite laminae, the sphene often containing central cores of rutile. This rock is regarded as an altered eclogite. (39b) is essentially a jadeite rock, the pyroxene forming 70 percent, lawsonite 20 percent, and glaucophane 10 percent of the thin section; sphene is accessory. In (56d) equigranular epidote and soda-pyroxene make up more than 90 percent of the rock, with interstitial glaucophane, sphene, chlorite, and opaque iron ore in minor amounts. Muscovite, calcite, albite, and chlorite pseudomorphous after garnet are accessory in (11e); the epidote, albite, and calcite tend to be associated.

CONCLUSIONS

A number of conclusions bearing on the vexed problems concerning the origin of glaucophane schists can be drawn from the North Berkeley material.

(a) The glaucophane schists and allied rocks are tectonic inclusions in a highly sheared serpentinite body. Some are as much as 80,000 cubic feet in volume.

(b) Solutions responsible for the development of the glaucophane assemblages were active at the time of emplacement of the serpentinite along the Hayward fault zone, since the adjacent Franciscan-Knoxville rocks also locally contain small amounts of glaucophane.

(c) At the time of intrusion the serpentinite was plastic; blocks of the included metamorphic rocks, at this stage completely crystallized and competent, were rotated and slickensided during their transportation upwards. Metasomatism involving inward transfer of Mg from the serpentinite was

probably responsible for the development of tremolite-actinolite sheaths around many of these blocks.

(d) Serpentinization of the original peridotite and recrystallization of the glaucophane rocks therefore were mainly completed at unknown depth prior to intrusion; but it is not clear if these processes were necessarily related either in time or as regards the source of the fluids concerned. The presence in the serpentinite of schists of such varied mineralogy suggests that evolution of the glaucophane-bearing assemblages may have been influenced by a wide range of physical and chemical conditions.

No genetic importance can be attached to the present field association of rock types in view of their allochthonous location within the serpentinite; but study of textures in thin sections reveals a consistent succession of mineral replacements. In this respect two distinct sets of minerals can be recognized in the glaucophane rocks:

(1) garnet, hornblende, pyroxene, and rutile, occurring in quantity in eclogitic and amphibole-rich rocks, or in small amounts as relict grains in the glaucophane schists. These minerals all show replacement by minerals believed to represent a lower grade of metamorphism.

(2) glaucophane, epidote, muscovite, chlorite, lawsonite, pumpellyite, and sphene which appear at some stage as alteration products of the preceding group. There are also minerals such as actinolite, albite, and stilpnomelane that seem to play no part in replacement processes.

On this evidence it is concluded that eclogites and hornblende-rocks have been converted by retrogressive metamorphism to form some of the glaucophane schists. Many of the well-crystallized and foliated schists that lack relics of older metamorphic facies may be accounted for as recrystallized sediments; for example, the quartz-albite-garnet-glaucophane schists are probably metamorphosed cherts, perhaps affected by Na-Fe metasomatism. However, a consideration of specific assemblages, as described on earlier pages, and their relationship to the occurrence of glaucophane indicates that there have been several lines of descent controlled by some variable metamorphic factor, or factors.

The formation of glaucophane seems not to be dependent upon any particular set of temperature-pressure conditions. Moreover, the amphibole is equally common in highly deformed and foliated rocks as it is in low-grade assemblages with weak foliation. In addition, glaucophane has developed in sedimentary rocks adjacent to serpentinite at a late stage of intrusion when earlier-formed glaucophane rocks were suffering tectonic transport. The presence and absence of glaucophane in otherwise identical mineral assemblages point to the same conclusion. The amphibole occurs as a replacing mineral in eclogites which are altering by retrogressive metamorphism to epidote-hornblende rock, and as well, makes large contributions in some epidote-muscovite-chlorite schists. On the other hand, many rocks of greenschist type containing fragments of garnet and soda-pyroxene indicating eclogitic parentage lack glaucophane. Without doubt these rocks have passed through the same stages of retrogressive metamorphism, and therefore through the same ranges of temperature and pressure as the associated schists which

possess a similar mineralogy but contain glaucophane in addition. The most obvious metamorphic variable that could alternatively promote or preclude formation of glaucophane under the same range of physical conditions is the composition of the pore solutions, as suggested by Turner (1947a) and Turner and Verhoogen (1951, p. 473). This could also explain much of the broad variation in mineralogy shown by the North Berkeley rocks. It accounts for the large number of permutations of three to five mineral phases which appear as variants of the total assemblage glaucophane-lawsonite-epidote-clinozoisite-pumpellyite-muscovite-albite-quartz-sphene. The potentialities of highly mobile solutions in causing extreme local changes in mineral composition are well illustrated in other exposures of the glaucophane schists in California. For example, Switzer (1945) and Borg (1954) described eclogites traversed by fractures filled with rutile, apatite, muscovite, and glaucophane; monomineralic veins of pumpellyite, epidote, lawsonite, glaucophane, actinolite, chlorite, pyroxene, albite, and even garnet are commonly found as products of metamorphic differentiation in Californian glaucophane schists.

Under these circumstances it is impossible to interpret any specific mineral assemblage as being a "subfacies" of a glaucophane schist "facies" in the manner applied by de Roever (1950) to comparable rocks from Celebes. All conclusions formed from a study of the North Berkeley rocks and from the literature on Californian glaucophane schists are contrary to the opinion expressed by de Roever (1950, p. 1463) that "the development of glaucophane in rocks of suitable chemical composition is controlled by special physical conditions, i.e. that there exists a separate glaucophane-schist facies." On evidence of microscopic texture and mineralogical associations it seems logical to equate the physical conditions governing the formation of the glaucophane rocks with those of the greenschist and epidote-amphibolite facies. Similarly, it is not possible to accept de Roever's deductive extrapolation (p. 1462) that "in California the development of glaucophane, etc. instead of the normal products of such metasomatic processes, like albite, etc. during or after this additive metamorphism, in the chemically adapted rocks, however must also have been controlled by physical factors, as indicated by the results of the investigations of the present author." The conclusion recently expressed by Schürmann (1953, p. 392) that introduction of glaucophane in the Californian schists was controlled by soda metasomatism is more compatible with the evidence from the North Berkeley area. But there is no evidence either for or against the commonly accepted idea that intrusions of serpentinite are the source of the solutions concerned.

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RELATION OF COAL RANK TO ORIGINAL DEPTH OF BURIAL IN WEST VIRGINIA*

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ABSTRACT. The relation between the fixed carbon percentage of the coals and the original thickness of cover was found by a regional study of southern West Virginia. This relation is useful in finding the probable rank of any deeply buried coal from analyses of coals near the surface. The relation can also be used to find the original thickness of sediments now eroded, and this was done for northern West Virginia and southern Pennsylvania to reconstruct an isopach map of the Dunkard Series. The good correlation between fixed carbon percentage and original depth of burial shows that horizontal thrust played a minor part in the metamorphism of the coals.

INTRODUCTION

West Virginia coal analyses were studied on a regional basis to learn the relation of fixed carbon percentage to original maximum depth of burial. As long ago as 1873 Hilt noted that there was an increase in the rank of coal with stratigraphic depth, and Reeves and Price (1950), Heck (1943), and Reeves (1928) have concluded that the major cause of changes in rank of coal is depth of burial (load metamorphism) rather than tangential thrust as proposed by White (1915 and 1925). Reeves (1928) analyzed stratigraphically separated coals in the Allegheny basin at 17 locations to learn the rate of increase of fixed carbon percentage with depth. He found values ranging from 0.27 percent to 1.91 percent per 100 feet with an average of 0.69 percent but did not find the variation of rate with change of rank, although he did recognize that such a variation did occur. The rate as found in a short stratigraphic interval will be affected by initial differences in organic matter in the individual beds which may cause variations larger than the changes in rank due to increased depth. Even if it were possible to learn the rate of increase of fixed carbon with depth there would be no direct means of correlating the fixed carbon percentage with original depth of burial. It is the purpose of this paper to find this relation between fixed carbon and original depth of burial and to show some of the applications of such correlation.

METHOD OF FINDING CORRELATION

Even though the method of carrying out proximate analyses has been standardized (Stanton, Fieldner, and Selvig, 1938; A.S.T.M., 1938), Heck (1943, p. 1210) has shown that analyses of the same samples by different laboratories show considerable variation. The analyses used for this study in West Virginia were all taken from Headlee and Nolting (1940), and those in Pennsylvania were from Fieldner, Cooper, and Osgood (1928). Proximate analyses are reported in terms of the weight percents of moisture, volatile matter, fixed carbon, and ash. Since the ash and moisture are not involved in the changes which have taken place in the organic components during metamorphism, the data were recalculated to a moisture- and ash-free basis.

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The coals found in mines and outcrops in West Virginia and southern Pennsylvania show an increase in fixed carbon content from west to east as shown in figure 1. This map was adapted from maps by Headlee and Nolting (1940), Reeves (1928), and Ashley (1928). The isocarb through any place is determined by the average of analyses of all beds occurring there.

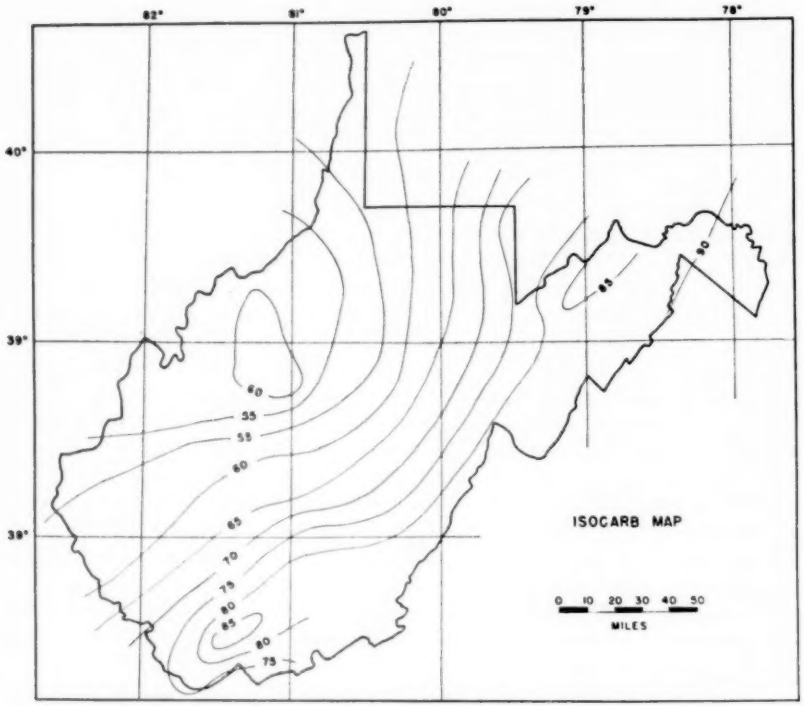

Fig. 1. Isocarb map showing lines connecting points where surface coals have equal fixed carbon percentage. Adapted from isocarb maps by Headlee and Nolting (1940), Reeves (1928), and Ashley (1928).

In order to learn the relation of fixed carbon percentage to original depth of burial, 311 analyses from 23 coal beds were compared with original depth of burial. To obtain the original depth of burial, isopach maps were made of the Pottsville, Allegheny, Conemaugh, and Monongahela series to show original thickness. While there are wide areas where erosion has removed one or more series or left only basal portions, there are usually neighboring areas where more complete sections can be used to extend isopachs reasonably across eroded areas. Reconstructed isopach maps of the Pottsville and Conemaugh were made from maps by Heck (1943), measured thicknesses (Price, Tucker, and Haught, 1938), and well records (Tucker, 1936, 1944; Martens, 1945), and the Allegheny and Monongahela isopach maps were made from the measured field sections and well records only. Since there

is reason to believe that uplift and erosion occurred in the southern part of the area before the northern part (Price, 1931), it was assumed that little or no Permian (Dunkard) sediments were ever present above the Pennsylvanian (Monongahela) in southern West Virginia. For this reason the area considered in finding the correlation was limited to West Virginia south of 38° 30′ N, and the thickness of Pennsylvanian sediments above each coal bed was taken as the original depth of burial. No data were included from the extreme southeastern part of the state where great thickening of the sediments and subsequent great erosion make isopach reconstruction very doubtful. The rate of change of fixed carbon with depth has been well studied in this part of the state by Heck (1943).

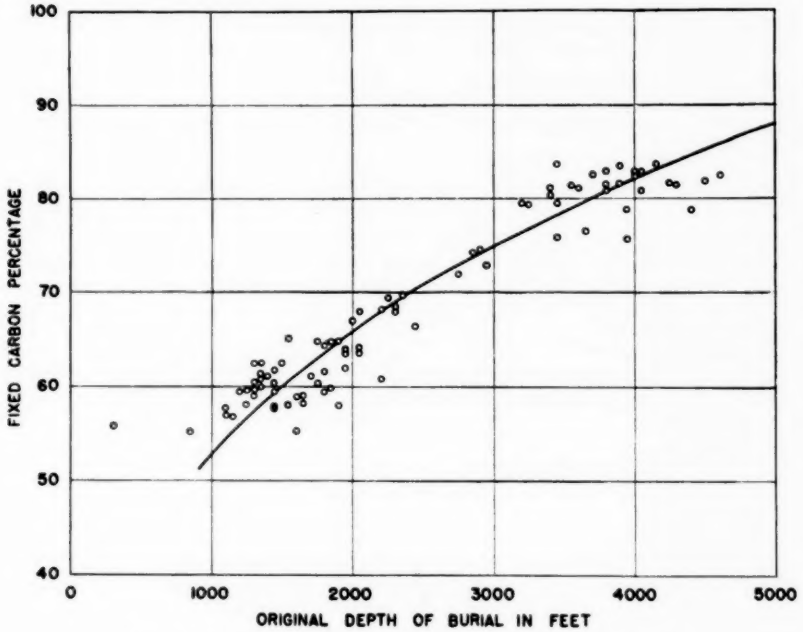

Fig. 2. Relation of carbon content to original depth of burial.

The coal analyses for each bed were averaged together by 15 minute quadrangles. All the analyses of samples of a particular coal bed taken over a quadrangle were averaged, and the original depth of burial of the coal bed at the center of the quadrangle was found from the isopach maps, taking into account the position of the bed within its series. Thus each bed occurring within a quadrangle gave a single point for the plot shown in figure 2. The method of making the isopach maps and the small lateral rate of variation of fixed carbon percentage within a single bed did not warrant any attempt to use areas smaller than quadrangles. It is pointed out that the lateral rate of variation within any individual bed is much less than the variations shown

in figure 1, where variations are due in large part to stratigraphic separation of the coals used for analysis across the area. In some quadrangles analyses were available from as many as 7 separate coal beds, whereas in others there were none. Each coal bed occurring within a quadrangle has, of course, a different original depth of burial depending on its stratigraphic position. In figure 2 are shown 85 points, each representing the average analysis and original depth within a quadrangle for one bed.

The scattering of points is due to errors in analyses, differences in original organic matter from bed to bed, and errors introduced by extending isopach lines from areas with known thicknesses into areas with no data to find the original maximum depth of burial. Each of these should cause a symmetrical scattering about a mean which should represent the best approach to the correct answer. The use of a large area and analyses from many coal beds should tend to give symmetrical rather than one-sided errors. However, the assumption that no Dunkard sediments ever existed over the study area, if mistaken, would cause the slope of the curve to be steeper than it should be since this would cause non-random errors.

The curve drawn through the points in figure 2 becomes a straight line when redrawn on logarithmic coordinate paper, and its equation is:

$$C = 5.77\ D^{0.32}$$

where C is the fixed carbon percent and D is the original depth of burial in feet. Since there are no data available to justify doing so, the equation should not be used outside the range of the curve drawn in figure 2. The equation seems to give values of fixed carbon which are too great for depths over 5000 feet and too small under 500 feet.

By differentiating the equation the rate of change of fixed carbon percentage per foot can be found in terms of original depth of burial:

$$dC/dD = 1.85 / D^{0.68}$$

This gives the slope of the curve of figure 2. Also by substitution the rate can be found in terms of carbon content:

$$dC/dD = 76 / C^{2.121}$$

Evaluation of this equation for several values of fixed carbon percentage is shown in table 1. The rates of change of carbon content with depth seem to fall in the same range as those found by Reeves (1928) although the average is greater.

Analyses from each bed generally gave plots parallel to the curve so that if a coal had, for instance, one analysis 4 percent below the curve, all analyses from this bed over the area would tend to be about this much below the curve. This is probably due to differences in original organic matter from bed to bed and shows uniformity within individual beds.

TABLE 1

Fixed Carbon Percentage	Increase of Fixed Carbon Percentage per 100 foot Increase in Depth
50	1.90
60	1.27
70	0.92
80	0.69
90	0.54

APPLICATIONS

This correlation can be useful in at least two ways. The probable analysis or rank of a coal bed at depth can be determined from analyses of a coal near the surface. To find the probable analysis of a coal which might occur at a depth of 1000 feet below a surface coal analyzing 60 percent, one would first find from figure 2 the original depth of burial corresponding to 60 percent, which is 1500 feet. The fixed carbon percentage at a depth 1000 feet greater, or 2500 feet, is then found to be 71 percent. The actual coal might vary widely from this due to initial differences of organic material or other unknown factors, but in the absence of any other information 71 percent would be the most probable value. In other areas or other basins of deposition there might be conditions which would cause the relation to be entirely different, so that the curve found for West Virginia coals may not apply to other coals. For instance, the change of fixed carbon percentage with depth may be due in part to increase of temperature with depth, and variations of the past depth-temperature gradient from area to area would cause changes in the fixed carbon-depth relation from that shown in figure 2.

The thickness of the beds eroded can be determined from the fixed carbon percentage of the coals. Heck (1943, p. 1222) has stated that the relative thickness of beds now eroded can be determined from the fixed carbon of the coals. To the extent to which the curve of figure 2 is valid, not only relative but also absolute thickness of eroded beds can be found.

RECONSTRUCTION OF THE DUNKARD

A reconstruction showing the original thickness of the Permian Dunkard Series was made from coal analyses in West Virginia north of 38° 30′ N and in southern Pennsylvania. This was done by averaging all analyses from each coal bed within a quadrangle and determining the original depth of burial for each average. From this depth were subtracted the thicknesses of all Pennsylvanian rocks above the coal bed to give the thickness of the Dunkard. The thicknesses as found from all beds in the quadrangle, if more than one, were averaged to give thickness at the center of the quadrangle. The results of treating each quadrangle in this manner are shown in figure 3. This reconstruction of the Dunkard is confirmed in a general way by Price (1931) who says that during Permian time the trough of deposition shifted to the north and west.

Since the areas considered in the two phases of this study do not overlap, none of the analyses used in the Dunkard reconstruction were used in figure 2. After the isopach map (fig. 3) had been completed, a new plot of original depth of burial versus fixed carbon was made using only those analyses involved in making the map. The average curve was, of course, identical to that shown in figure 2 since the thicknesses were determined from figure 2. However, the general scattering of points was only half as much because of the fact that the thicknesses were adjusted to fit the curve and did not add to the random scatter caused by variations in original organic matter or analyses. This means that about half the scattering of points seen in figure 2 is the result of errors in the isopach maps of the Pennsylvanian series from which original thicknesses were found.

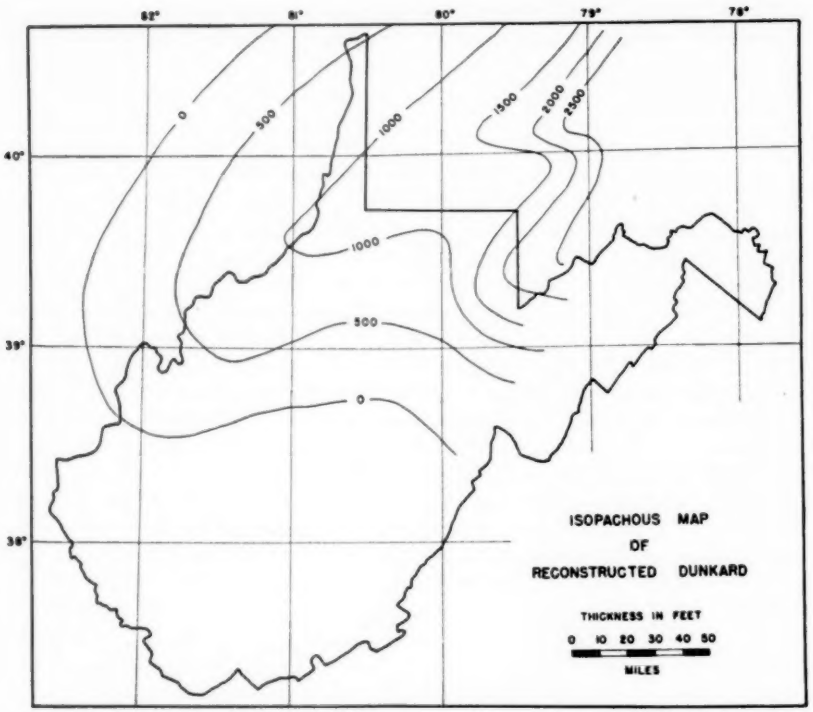

Fig. 3. Isopach map of Dunkard Series reconstructed to show original thickness.

CONCLUSIONS

There is a good correlation between rank of coal and original depth of burial showing that depth of burial is the major factor in coal metamorphism rather than horizontal thrust associated with orogeny. The increase of coal rank toward the Appalachians (fig. 1) is caused by the greater depth of burial of coals in the deeper parts of the basin of deposition near the mountains. Heck (1943) has shown that the reversal of the isocarbs in the southeastern part of West Virginia is due to a decrease of overburden and that there is no correlation of rank with structure or probable deforming stress.

The type of analysis used in this study can be used to find the probable rank of coal at depth from surface coal analyses, and can be used to find the original thickness of beds now eroded.

ACKNOWLEDGMENTS

The writer is indebted to Dr. P. H. Price, State Geologist of West Virginia, for suggesting the problem and to Dr. C. M. Nevin of Cornell University for valuable aid throughout the work. The writer is also indebted to the West Virginia Geological Survey for the use of office facilities during the summer of 1948.

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LATE MIOCENE MAMMALS FROM OAXACA, MEXICO

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ABSTRACT. Mammalian remains from tuffaceous sedimentary rock in Valle de Nejapa, Oajaca, are the first vertebrates older than Pliocene to be recorded from Mexico or Central America. The genera *Merychippus and ?Oxydactylus* are represented. Though the fossils inadequately represent the fauna, they are not older than Hemingfordian (middle Miocene) nor later than Barstovian (late Miocene). The size and height or crown in the cheekteeth of *Merychippus* is more suggestive of Barstovian. A new faunal name, *El Gramal*, is proposed.

A recent discovery (January and February 1952) of Miocene mammalian remains along the Pan-American highway about halfway between the cities of Oajaca and Tehuantepec gives us our first evidence of pre-Pliocene continental vertebrates between the Panama Canal and United States-Mexico border. These specimens were found by J. Wyatt Durham and A. R. V. Arellano who, with Joseph H. Peck and the writer, were on a project sponsored by the Associates in Tropical Biogeography at the University of California, to search for evidence for a Tertiary marine connection across the Isthmus of Tehuantepec (Durham, Arellano, and Peck, 1952). Olson and McGrew (1941) have reported a rather meager assemblage of Hemphillian (early middle Pliocene) species from western Honduras, but these are related to Pliocene species in the United States and throw no light on the earlier Tertiary record in Central America and southern Mexico.

Unfortunately, only the genera can be identified in these Miocene specimens, but additional careful search in the formation should yield better materials and give us a much clearer picture of the late Miocene land mammals in that region.

OBSERVATION ON THE STRATIGRAPHY

The specimens were found near the ranch house El Gramal south of the village of Nejapa in the northwest part of Valle de Nejapa. El Gramal is on the Pan-American highway near kilometer 668 where the highway crosses Arroyo El Gramal. This area is approximately halfway between Oajaca and Tehuantepec.

The first discovery was part of an upper cheektooth. This was found by Arellano in a sandy conglomerate member in a road cut on the east side of the highway 1120 meters south of ranch house El Gramal (loc. V5207). The second and most significant find was by Durham in a dry gully about 300 meters west of El Gramal. It was a grayish brown tuffaceous concretion with black bone exposed. The specimen was found in the middle of the gully but its original source could not have been more than 15 meters upstream (V5208).

We did not have time to map or even adequately prospect the tuffaceous sediments in Valle de Nejapa. There are excellent exposures in the road cuts between the village El Camarón and El Gramal. The valley containing these Miocene sediments is probably 15 kilometers long and perhaps 3 kilometers wide; the formation is about 200-300 meters thick. The best exposures are to the southwest of Camarón where J. W. Durham (observation from air) has estimated that they may continue for at least 15 kilometers farther. This is

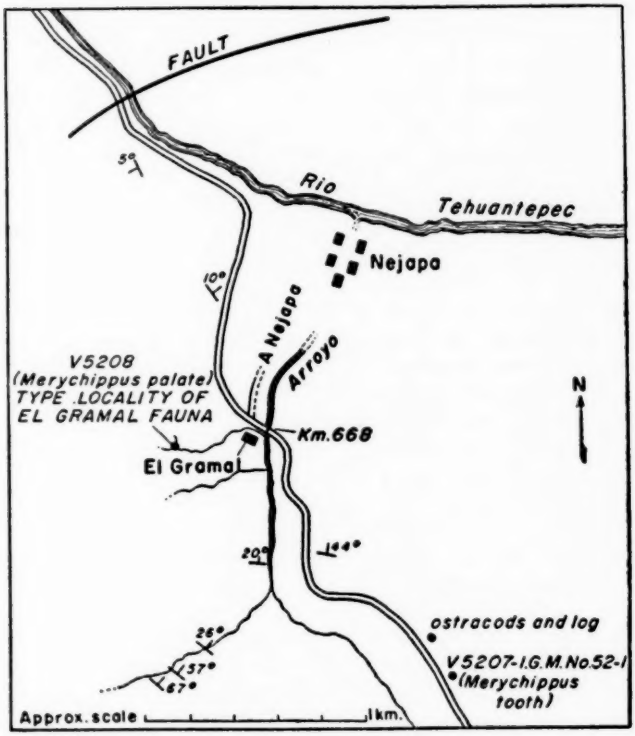

Fig. 1. Sketch of type locality of El Gramal fauna. Not drawn to scale. Drawn by Owen J. Poe.

a rather open, rolling, brushy pasture land. The gravel residue on the surface makes footing insecure in many places. Exposures could be seen to the south of El Camarón and beyond the Rio Tehuantepec north of Nejapa. These sedimentary rocks are in fault contact with igneous rocks at the northern edge of the valley.

The formation is predominately tuffaceous and composed of folded claystones, sandstones, and conglomerate members. The tuffs are rhyolitic or dacitic with hornblende, biotite, and very fine glassy materials. This is particularly true of the finer sands and claystones which vary from grays to greens and to grayish brown in color. The coarser sandstones are made up of quartz, feldspar, plagioclase and biotite flakes with opal cementation. Some heavier conglomerate members were also observed.

Locally and at different times there were lakes or ponds that appear to have dried up as indicated by the presence of ostracods, indurated mudcracks and gypsum. Fossil wood in these deposits was not uncommon.

DESCRIPTION OF EL GRAMAL FAUNA

Merychippus

The best specimen is part of a palate with most of the right maxillary and both premaxillaries preserved, right I^{1-3} (anterior parts of I^{1-2} broken off), C, $P^1 - M^3$ in place, left I^{1-3} (I^1 broken), C, $P^1 - P^3$ in place; proximal ends of right metatarsals II and III, distal end of femur, part of tibial shaft, U. C. Mus. Pal. no. 42293, U. C. loc. no. V5208.

This was an old individual with the teeth heavily worn. The palate is slightly crushed with the left side shifted a few millimeters forward. The exposed lateral lower surface of the maxillary indicates that the lacrimal fossa was not deep.

Length from anterior angle of P^2 to posterior edge opposite postfossette on M^3 111.4 mm; anterior angle of P^2 to posterior edge opposite postfossette on P^4 60.5 mm; anterior edge of M^1 opposite prefossette to posterior edge opposite postfossette on M^3 52.4 mm; diastem between I^3 and C 14.5 mm; diastem between C and P^1 26.2 mm; width between outer basal borders of canines 33.7 mm; faint remnant of base of cup in I^3; canine little worn, anteroposterior and transverse basal dimensions of canine 9.4 mm x 6.9 mm; P^1 large but heavily worn, length 13.8 mm; other premolars and molars worn to within 9 mm of base on labial side and 4 mm of base on lingual side; P^2 with prefossette opening lingually through postprotoconal valley; inner tip of postprotoconal valley isolated as small enamel lake in P^3, P^4, and M^1.

The El Gramal specimen is slightly smaller than Cope's type of *Merychippus sejunctus* (Osborn, 1918, pl. 16, fig. 3) from the Pawnee Creek of northeast Colorado. The Pawnee Creek specimen is not as heavily worn as the one from Mexico but they show a marked similarity not only in size but in the prefossette opening lingually through the postprotoconal valley on P^2 and in the isolation of the inner tip of the postprotoconal valley in P^3, P^4 and M^1. These features are foreshadowed in some of the specimens of *Merychippus primus* (Osborn) from the Sheep Creek Hemingfordian (middle Miocene) of western Nebraska.

The first specimen found includes the prefossettes and postfossettes of an upper cheektooth. These structures are preserved to their bases. The edges of the fossettes show only slight wear. The tooth fragment is curved and it contains cement in the fossettes. The height from the base to the top of the fossettes is 37 mm. This tends to indicate that the height of crown in this tooth was more than 40 mm and hence is referable to a Barstovian (late Miocene) age. The length from the anterior edge of the prefossette to the posterior edge of the postfossette is 17 mm. Inst. Geol. Mexico, no. 52-1. U. C. loc. no. 5207.

?Oxydactylus

In the concretion with the *Merychippus* palate and limb bones is the distal 135 mm of a small camelid cannonbone. This specimen looks very much like that of certain *Oxydactylus* species from the Great Plains region. The distal ends of the two shafts diverge slightly and are not fused, though they probably were coalesced in the proximal half of the bone. Width across face

of distal facets 19 mm; width of shaft 20 mm above facet 15 mm. U. C. Mus. Pal. no. 42294.

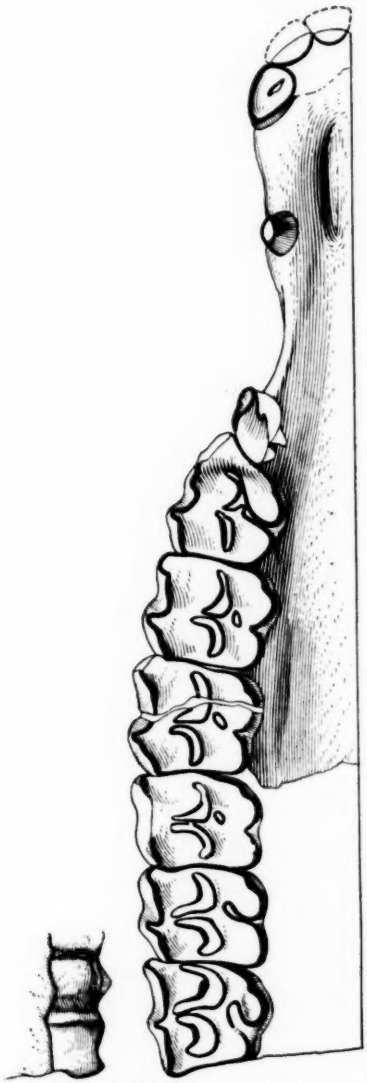

Fig. 2. *Merychippus*, right $I^1 - M^3$, part of palatine surface, and labial view of M^3, U. C. Mus. Pal. no. 42293. 2/3 natural size. El Gramal fauna, Valle de Nejapa, Oajaca, Mexico. Drawn by Owen J. Poe.

CONCLUSIONS

The tuffaceous sediments in the Valle de Nejapa are not named because of the incomplete evidence on the formation available. The vertebrate remains

are referred to as the *El Gramal* fauna (new name). The type locality is 300 meters west of El Gramal, Kilometer 668 Pan-American highway. U. C. Mus. Pal. no. V5208.

Though camelids referable to the genus *Oxydactylus* occur in the early and middle Miocene in the United States, it is thought that representatives of the genus may have survived later in lower latitudes. The *Merychippus* specimens though incomplete are suggestive of a Barstovian (late Miocene) age. This is evidenced in the size and height of crown in the cheekteeth. The beds are not older than Hemingfordian (middle Miocene) nor later than Barstovian (late Miocene).

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REVIEWS

Carte géologique de la Tunisie (1:500,000). Two sheets, appr. 30 x 44 in.; *Notice explicative* (143 p., 14 pls.); by G. CASTANY. Tunis, 1952 and 1953 (Direction des Travaux Publics, Service Géologique).—One of the many valuable results of the International Geological Congresses is the appearance of new maps and general reports on the geology of the host countries. The 19th Congress was no exception, for it brought about the preparation of Regional Monographs for Algeria, Tunisia, and Morocco, and of 2 sheets of a geological map on 1:2,000,000 of Northwest Africa. In addition, new geologic maps of each of the major political units on 1:500,000 (1:400,000 for the Spanish zone of Morocco) were undertaken; of these only the map for Algeria (a second edition, 6 sheets) was completed and generally available by the time of the Congress.

Two sheets of the new (2nd edition) map of Tunisia also appeared at or just after the Congress; these cover virtually the entire Regency plus considerable areas of eastern Algeria. A third sheet, to cover the southernmost tip of the country (all flat-lying Cretaceous or sand dunes) and adjacent parts of Algeria and Tripolitania, will complete the map. More recently an explanatory booklet, describing the map units in some detail and summarizing also the structure, the paleogeography, the orogenic history, and (very briefly) the mineral deposits, has appeared; in conjunction with the Regional Monographs it will be very useful to users of the map. Map and booklet have been prepared by M. Gilbert Castany, Director of the Geological Survey of Tunisia, and his staff.

The new map of French Morocco (6 sheets) was only in the proof sheet stage in 1952, but should be available shortly. The map of Spanish Morocco (1 sheet) is obtainable from the Comisión de Estudios Geológicos de Marruecos at Madrid.

JOHN RODGERS

Evolution and Geography: An Essay on Historical Biogeography with Special Reference to Mammals; by G. G. SIMPSON. Condon Lectures, Oregon State System of Higher Education. P. 64, 30 figs.; 10 tables. Eugene, 1953 ($1.00, paper cover) (also available at American Museum Book Shop, New York 24, N. Y.).—This exceptionally lucid presentation of the historical aspects of animal distribution drives home fundamental principles with numerous graphs, charts, and humorous drawings. Phenomena of migration, isolation, and convergent evolution are illustrated by the histories of the South American and Australian mammalian faunas. Characteristics of faunal interchange by corridors, filter bridges, and sweepstake routes are succinctly described. The relationship of faunal readjustments following interchange are exemplified by the later Cenozoic history of the Americas; tendency to migrate and ratio of survival to extinction are shown to be correlated with the source area of the various elements involved. Relationships of geographic source, antiquity within a given region, and geographical affinities of animals are illustrated by clear-cut examples, thoroughly documented by the fossil record. The principles of faunal analysis are then applied to North American land mammals in somewhat greater detail. Finally the measurement of and

significance of faunal resemblances are considered, and the implications of biogeographic data for theories of paleogeography are briefly treated.

References are given to more detailed analyses of various topics so that the interested student may pursue the subject. Although intended as an introduction to the field, the clarity of Dr. Simpson's exposition should make this both pleasant and profitable reading even for the seasoned biogeographer.

JOSEPH T. GREGORY

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